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TECHNICAL NOTE

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ERECTABLE YAGI DISK ANTENNAS FOR SPACE-VEHICLE APPLICATIONS

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ERECTABLE YAGI DISK ANTENNAS FOR SPACE-VEHICLE APPLICATIONS

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SUMMARY

Methods are given for the design of four-element arrays of uniformly spaced Yagi disk elements having approximately 18-db gain over a 30-percent bandwidth and with peak sidelobe levels of less than -10 db. The allowable mechanical tolerances on such structures for application as space erectable antennas are stated. Working erectable models having package ratios up to 12 to 1 are described.

INTRODUCTION

One of the major problems that occurs in space-vehicle communications is that of achieving sufficient radio frequency (RF) system gain for wide-band data transmission. A possible solution to this problem is the use of a high-gain directional antenna on the space vehicle. The use of such antennas is limited by three major factors. First, for space communications the approved or suggested channels are in the range from 960 mc to 2300 mc. In this band, and particularly for the lower frequencies, an antenna of relatively large size is necessary to achieve high gain. Second, since high gain results in narrow beamwidths, a precise stabilization and antenna pointing system must be employed on the vehicle. Third, it is not possible to have large external surfaces on space vehicles during the launch phase since such surfaces create an intolerable amount of drag. Therefore, erectable antennas, which are stored during launch and released when the additional drag becomes small, are required to provide appreciable gain. Because narrow-beamwidth antennas require a precise and sophisticated control system, the choice of a particular gain level for a given vehicle antenna must be a compromise between desired RF system gain and the antenna-pointing-system capability. For the present design study a nominal gain level of 20 db (14° beamwidth) was arbitrarily chosen as a value that would give a significant increase in space vehicle RF system performance without requiring unusual complexity in a control system. Also the frequency band from 1427 mc to 1435 mc was chosen as typical of the general space frequency region mentioned previously.

At the frequencies and gain levels chosen there is a wide latitude in the choice of types of antennas. One particular approach is the use of an array of Yagi disk elements. This type of element is of interest because of its broadband properties. These properties allow large physical tolerances on the structure if it is used in narrow-band applications. Since a lightweight flexible structure is required for an erectable antenna, the tolerance properties of the Yagi disk structure appeared very favorable. The use of an array to achieve these moderate gain levels allows beamwidth switching from wide to narrow by simple methods. The ability to change beamwidth could be very useful for space-vehicle trajectories which include both small and large distances from the earth.

The primary objective of this report, therefore, is to present techniques for arraying Yagi disk elements which have uniform disk diameters and disk spacings. Secondary objectives are to state the tolerances that are necessary on such structures and to describe the performance of working erectable models.

SYMBOLS

b	ground-plane length
D	diameter of disk directors
E	electric field of antenna
f	frequency
H	magnetic field of antenna
h	height of feed bucket above ground plane
L	total length of antenna element
l_1	distance from ground plane to feed dipole
l_2	distance from feed dipole to first disk director
s_a	spacing between array elements
s_d	spacing between disk directors
s_f	spacing between feed dipoles

λ wavelength

λ_o wavelength at design frequency of 1435 mc

DESIGN OF YAGI DISK ARRAYS

General

One of the major problems that usually occur in the design of antenna arrays is that of compensating for the mutual coupling between elements. However, if the mutual coupling is small for a particular element, the array pattern can be determined from the element pattern by simple pattern multiplication (ref. 1). The uniformly spaced Yagi disk element, as shown subsequently, exhibits low coupling properties for element spacings as small as 1.25λ.

Arrays of elements having relatively broad patterns (dipoles, slots, etc.) spaced 1.25λ usually have very high sidelobes and grating lobes. However, for arrays of highly directive elements (i.e., the Yagi disk antenna), low-sidelobe-level performance can be achieved by the proper adjustment of the array factor and the sidelobe characteristics of the element pattern. Since the array factor can be simply adjusted by changing the spacing between elements, low sidelobe levels in arrays of directive elements can be achieved by tailoring the element pattern (primarily the position and amplitude of the sidelobes).

One possible method of tailoring the element pattern has been shown by Sengupta (ref. 2), where the Yagi element sidelobes were reduced by slightly tapering the phase velocity along the structure length. (The element he used was at least 4λ to 6λ long.) However, for the 2λ to 4λ long elements under consideration, very little change in the phase velocity can be accomplished by using this technique since the tapers proposed are too slight to give significant results.

As shown subsequently, the sidelobe levels and sidelobe positions for short elements are primarily determined by the details of the feed. In fact, tailoring of the element pattern can be accomplished by adjusting the dipole spacing, the distance to the first disk, and the addition of shields around the feed.

In summary, then, the design of Yagi disk arrays is accomplished by proper adjustment of all details of element design in addition to adjustment of the array factor. Only by proper attention to all of these factors can a broadband compact-array design be achieved.

Feed Design

There is some latitude in the choice of feeds for a Yagi disk element. However, the feed consisting of both a vertical and a horizontal array of two dipoles, as shown in figures 1 and 2, was chosen for two primary reasons. First, the space inside the dipoles provides a convenient volume for storing the disk in an erectable element and, second, the two pairs of dipoles provide polarization diversity. A certain amount of experimental adjustment of the dipole spacing s_f is necessary along with the adjustment of the distance to the first disk l_2 in order to feed the structure properly. In general, however, it has been found that the spacing s_f must be in the order of 0.5λ, and the spacing l_2 should be in the order of 0.25λ. Further discussion of these dimensions is given in the section entitled "Effects of Feed Scattering on Element Patterns." It is not necessary to adjust the dipole to ground-plane spacing l_1 when the parasitic elements are in place. Nominally this spacing is chosen to be 0.25λ and only a simple adjustment of this value without the disks is required to achieve maximum gain.

The basic dipole dimensions are given in figure 3. The impedance plot (assuming no coupling) of only one dipole is given in figure 4 since this is sufficient information for designing an impedance matching device when two dipoles are connected in parallel.

The average measured gain is approximately 6 db over the frequency range from 1250 mc to 1750 mc.

Yagi Structure Design

To obtain an end-fire pattern from a Yagi type of antenna requires the adjustment of a number of parameters. These parameters include the disk diameter and disk spacing. It has been shown (ref. 3) that the surface wave on the structure, for satisfactory operation, must be a slow wave having a phase velocity less than the velocity of light. To meet this requirement and to achieve nearly optimum gain, the following range of the structure parameters is necessary: The disk spacing s_d must be about 0.15λ to 0.40λ and the disk diameter D must be in the order of 0.20λ to 0.35λ. In general, it is possible to make a decision on both of these parameters independently (ref. 3).

For the short elements under consideration herein, the beamwidth and gain are essentially determined by the Yagi structure and are relatively independent of the particular feed configuration. Therefore, to determine more detailed design information on the Yagi structure, measurements were made over a 550-mc bandwidth about a design frequency of

1435 mc on a nominal structure (fig. 5) using a typical feed. The characteristics of this model are given in table I. There were two general parameter variations. First, the diameter D of the disk was varied from 2.25 inches ($0.274\lambda_0$) to 3.0 inches ($0.364\lambda_0$) in 0.25-inch steps while the disk spacing was maintained at 2.0 inches ($0.243\lambda_0$). The results of these measurements are given in figure 6. (The beamwidth given is the average E and H plane beamwidth. In general, these are nearly equal. The sidelobe level given is the maximum value regardless of plane of location.) Second, the spacing was varied from 1.5 inches ($0.1825\lambda_0$) to 2.5 inches ($0.304\lambda_0$) in 0.50-inch steps with the diameter fixed at 2.5 inches ($0.304\lambda_0$). The results of these measurements are given in figures 7 and 8.

An analysis of figure 6 clearly shows that the disk diameter is a very critical parameter in the structure. Several important features of these data should be noted. First, by reducing the size of the disks the sidelobe level can be reduced but beyond a certain point the beamwidth of the structure will broaden and result in a loss of gain in the structure. Second, the data obviously demonstrate that there are cutoff conditions on the structure as a function of frequency where the pattern starts to break up and the sidelobe level approaches the level of the main lobe ($D = 0.375\lambda$). As a result a diameter of 2.5 inches ($0.304\lambda_0$) can be chosen as the best compromise between sidelobe levels and gain for operation at a center frequency of 1435 mc.

An inspection of figures 7 and 8 shows that this structure is very insensitive to changes in disk spacing. In fact any spacing over the ranges of variation would be acceptable as an element design. A particular value of s_d of 2.0 inches as a nominal value was chosen for array purposes since this spacing, as shown later, resulted in good array sidelobe performance over wide bandwidths.

Effects of Feed Scattering on Element Patterns

Although the general dimensions of the feed have been stated previously, a more thorough investigation of the effects of changing the dipole spacing s_f and spacing to the first disk l_2 was necessary to gain an insight into how the feed affects the element pattern. Therefore, the element described in table I was used to perform the following experiments. First, the distance from the first disk to the feed was varied in 0.50-inch steps from 1.5 inches ($0.1825\lambda_0$) to 2.5 inches ($0.304\lambda_0$) while the spacing between the other disks remained constant. The results of these measurements over the frequency range from 1200 mc to 1750 mc are shown in figure 9. Next, a 12-inch ground plane was used with the element listed in table I except that the spacing between the dipoles was varied from 4 inches ($0.486\lambda_0$) to 6 inches ($0.728\lambda_0$) in

1-inch steps. The results of these measurements are shown in figure 10. The varying of the distance to the first disk apparently has very little effect upon the element pattern and therefore could be placed anywhere in the range described. However, changing the dipole spacing has a major effect upon the element sidelobe level but does not change the main lobe of the patterns appreciably. The value of 5 inches ($0.608\lambda_o$) was chosen since this value appeared to be the smallest possible spacing consistent with the mechanical arrangement of the feed. It is important to note that these data support the hypothesis that the direct feed radiation and scattering from the first disk essentially determine the element sidelobe level, whereas the disk diameter and disk spacing determine the beamwidth and gain.

FOUR-ELEMENT YAGI DISK ARRAYS

The design of arrays of Yagi disk elements, as stated previously, consists primarily of adjusting the element pattern and array factor to achieve a low sidelobe design over wide bandwidths. Initially arrays were constructed with the elements discussed previously (see table I), and because of particular sidelobe levels and sidelobe locations in the element patterns, low array sidelobe levels were difficult to obtain. Numerous patterns were measured at various element spacings for the array, and some designs were obtained with element spacings of 1.72λ or higher. This resulted in a relatively large structure with high average sidelobes (7 to 8 db). The spacing between elements could be reduced; however, the bandwidth over which the array sidelobes were less than -10 db was fairly small. It was then found that the details of the element-pattern sidelobes could be favorably changed by the addition of shields or buckets around the feeds, as shown in figure 11, along with a considerable reduction in the ground-plane length. These changes resulted in a significant improvement in the array performance and also made the array compact in size.

To demonstrate the use of the shields around the feed structure to tailor the element pattern, patterns were measured over a 550-mc range on a four-element array having the dimensions of table I and an element spacing of 12 inches. The results of these measurements are given in figure 12. These data show two important facts. First, the addition of shields causes little effect upon the beamwidth of the array pattern. Second, the shields greatly increase the bandwidth over which low sidelobe levels can be obtained.

To demonstrate the use of the array factor to tailor the array parameters, the array spacing was varied from 11 inches to 14 inches. These data are presented in figure 13 and show that significant reductions in array sidelobe levels can be achieved by the proper selection of spacings. The nominal gain of the four-element array is approximately 18 db from 1300 mc to 1700 mc.

Pattern Calculations

It was previously stated that the coupling between uniformly spaced Yagi structures is relatively low for spacings as small as 1.25λ. The existence of low coupling between the Yagi structures themselves can be deduced upon inspection of near-field measurements of single elements given in reference 3. However, some question about direct feed coupling in the array design can arise since the ground planes are small and the spacing between dipoles in adjacent feeds is less than a wavelength. In addition the thought that the feed shields used to tailor the element patterns are merely reducing the feed coupling can also arise. To resolve these questions, calculations of array patterns using measured element patterns and the uncoupled pattern multiplication theory were made for shielded and unshielded feeds. A comparison of calculated array patterns with measured array patterns is shown in figure 14. Since quite good agreement between measured and calculated values was obtained over a broad frequency range for the shielded and unshielded feeds, it can be concluded that the shields do not act as feed decouplers and can be used as a method of pattern tailoring. Therefore, for arrays of the type of element under consideration, it is theoretically possible to design the array if the pattern characteristics of one element are known.

Erectable Elements

One of the basic problems in the design of erectable structures for space vehicles is to meet size limitations without unduly complicating the erection technique. A simple technique for erection is found in some structural materials which upon compression and release will return to their original size and shape. With this erection technique, five major conditions are to be satisfied by a space erectable Yagi disk antenna element: First, only the director assembly of the element will be erectable; second, the supporting structure must be a material that can be packaged to a ratio of 8 or 10 to 1 and, when released, be inherently self-erecting; third, this material must be lightweight and have a low dielectric constant; fourth, the erection of the element must be within the allowable tolerances (discussed subsequently); fifth, the element must retain the allowable tolerances in a space environment. These five conditions are all directly related to the supporting structure material and the ability of this material to meet the tolerance requirements. From a review of available information on materials with high resilience and elasticity and with a low dielectric constant, polyether flexible urethane foam was selected as the supporting structure for the erectable Yagi disk antenna elements.

Since the array performance can be computed from the single-element performance, only single erectable elements are described. However, the dimensions used are those necessary for an element in a four-element array having 20-db gain and low sidelobes.

The self-erection technique has been demonstrated with several erectable Yagi disk antenna elements, one of which is shown in figure 15. Briefly, the elements consist of dipole—ground-plane units made of formica printed circuit board and director assemblies made of brass or aluminum-foil disks separated by polyether flexible urethane foam spacers. The precut and shaped foam acts as the supporting structure for the disks and as the erecting mechanism for the complete director assembly. The height of the dipole—ground-plane units is made to correspond with the minimum height the foam can be compressed without excessive compression load. The director assemblies are packaged into these units by compressing the foam along the assembly axes (fig. 15).

A more detailed discussion on the erectable elements and the effects of a space environment on these elements is presented in reference 4.

Tolerances

In the study of the effects of tolerances in the array structure it is assumed that the disk diameter, disk thickness, and spacing between elements are fixed since only the disk structure is erectable. Therefore, only two-dimensional variations could occur on the erectable structure - namely, the spacing between disks could be in error and the cantilever foam structure could be deflected from the normal position by external loads. The effects of an error in spacing were measured on both a single rigid element and a rigid four-element array. The results of these measurements are shown in figures 7 and 16 where the disk spacing was changed ± 25 percent from the design value. An inspection of the data presented demonstrates that the structure is relatively insensitive to large changes in disk spacing and, in fact, could operate with a partial failure in the erectable part of the structure.

Measurements were made to determine the effects on the array of deflecting the elements so that the element tips moved ± 1 inch and ± 2 inches. For deflections up to 1 inch, no significant effect upon the array patterns was observed. For deflections as large as 2 inches the beam tilted slightly; however, the major effect was to increase the sidelobe level and to make the sidelobes asymmetrical.

The main conclusion to be drawn from the tolerance study is that rather large variations in the array structure can be allowed without serious loss in antenna performance.

Comparison of Erectable and Rigid Elements

Radiation patterns of two erectable elements were measured and compared with those of a rigid antenna. The results of these measurements are given in figure 17. It can be seen that the antennas are nearly identical in performance.

CONCLUDING REMARKS

It has been demonstrated that for element spacings as small as 1.25λ there is little mutual coupling between elements and as a result the design of arrays of Yagi disk elements reduces to the problem of element pattern control. Therefore, the data obtained on tolerances can be scaled for use anywhere in the space frequency band from 960 mc to 2300 mc.

A method of element pattern control, the use of buckets around the feeds, has been demonstrated. Reduction of the array sidelobe levels by 2 db or 3 db has been achieved by this method over a 30-percent bandwidth.

An erectable model has been constructed and tested which was capable of package ratios up to 12 to 1. This model demonstrates the self-erection technique for space-vehicle antennas. This model has electrical properties which closely approximate the performance of rigid models.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., June 29, 1962.

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2. Sengupta, Dipak L.: On Uniform and Linearly Tapered Long Yagi Antennas. IRE Trans. on Antennas and Propagation, vol. AP-8, no. 1, Jan. 1960, pp. 11-17.

3. Ehrenspeck, H. W., and Poehler, H.: A New Method for Obtaining Maximum Gain From Yagi Antennas. IRE Trans. on Antennas and Propagation, vol. AP-7, no. 4, Oct. 1959, pp. 379-386.

4. Croswell, W. F., Gilreath, M. C., and Vaughan, V. L., Jr.: Self-Erecting Space Antennas. IRE Trans. on Space Electronics and Telemetry, vol. SET-8, no. 2, June 1962, pp. 139-142.

TABLE I.- ELEMENT DIMENSIONS

Number of disks	11
Distance l_2 from dipole to first disk	2.0 in. $(0.243\lambda_o)$
Distance s_f between feed dipoles	5.0 in. $(0.608\lambda_o)$
Length b of ground plane	8.0 in. $(0.972\lambda_o)$
Height l_1 of feed dipole above ground plane	2.0 in. $(0.243\lambda_o)$
Design disk diameter D	2.5 in. $(0.304\lambda_o)$
Design distance s_d between disks	2.0 in. $(0.243\lambda_o)$
Design frequency	1435 mc $(\lambda_o = 8.24$ in.)
Test frequency range	1200 mc to 1750 mc
Bucket height	2 in.

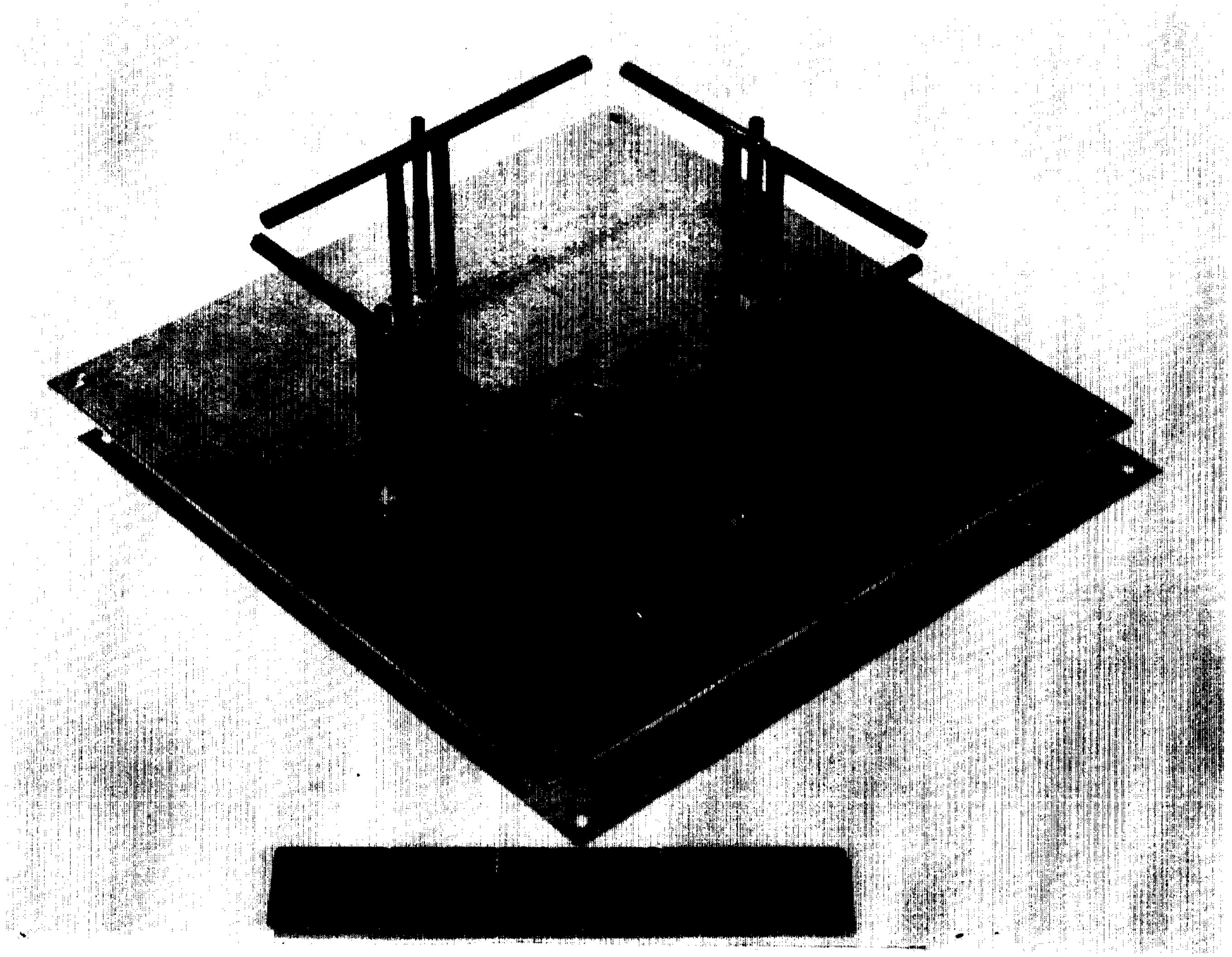


Figure 1.- Bipolarized feed for Yagi disk element. L-61-5316

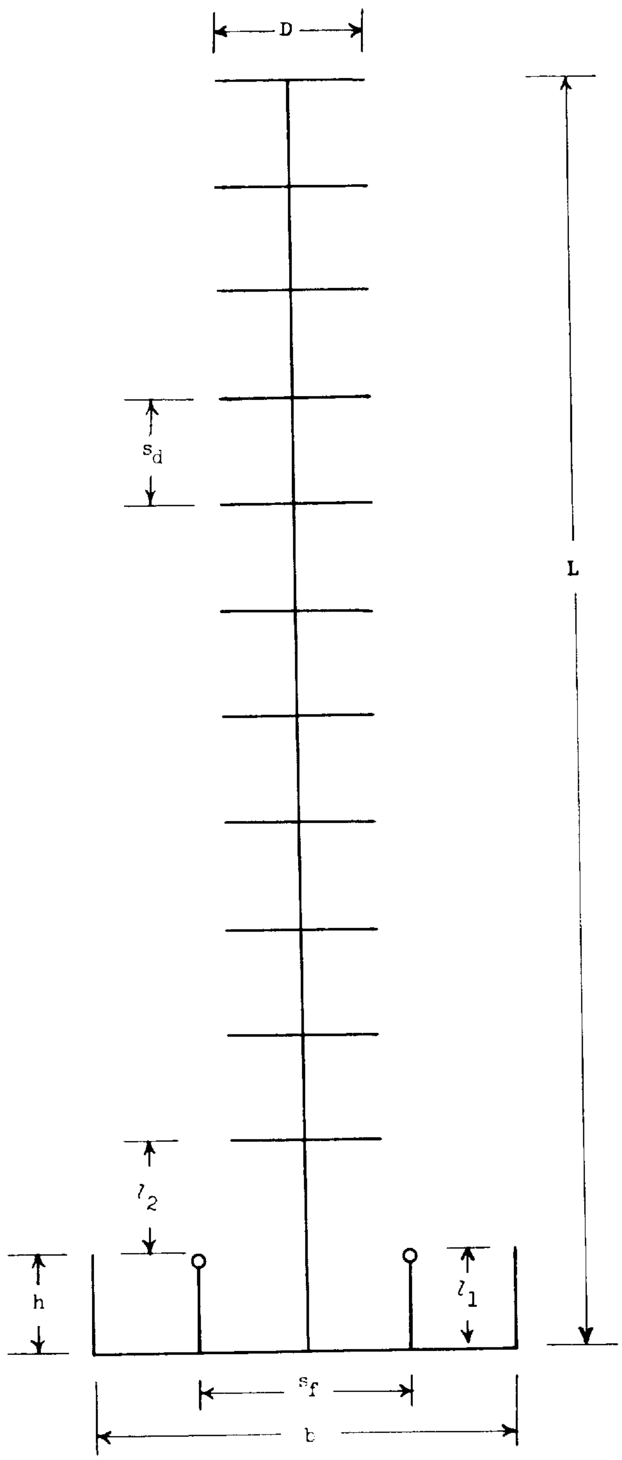


Figure 2.- Diagram of Yagi disk element.

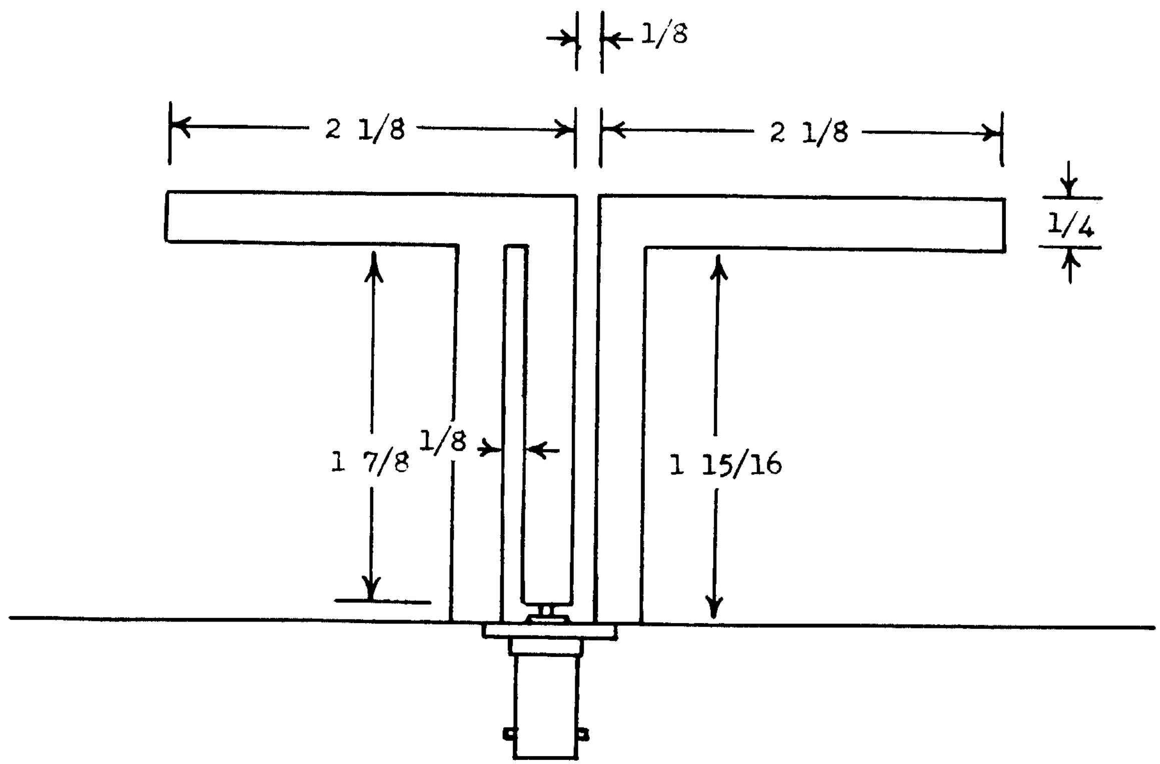


Figure 3.- Feed-dipole dimensions (in inches).

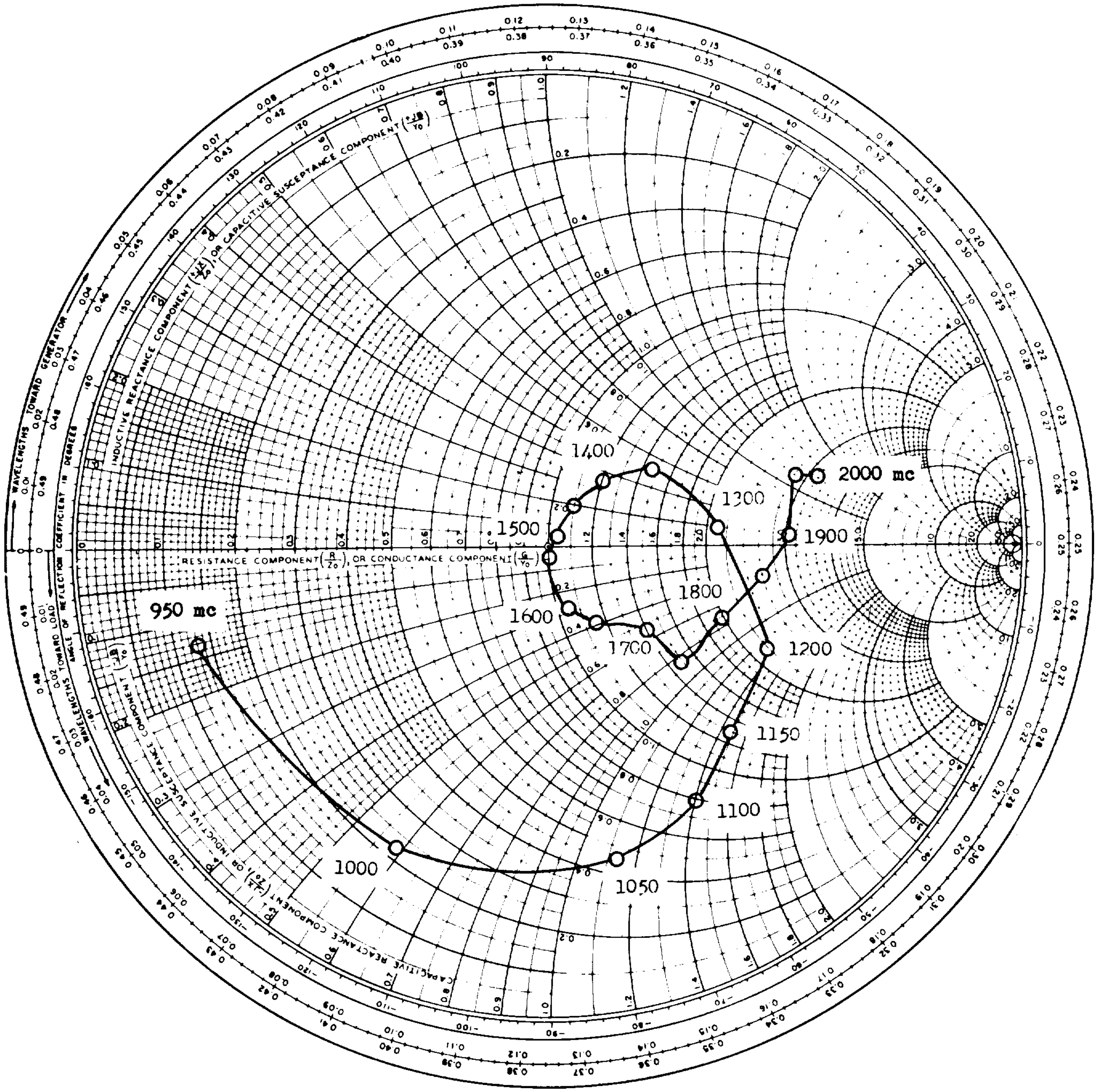


Figure 4.- Feed-dipole impedance.

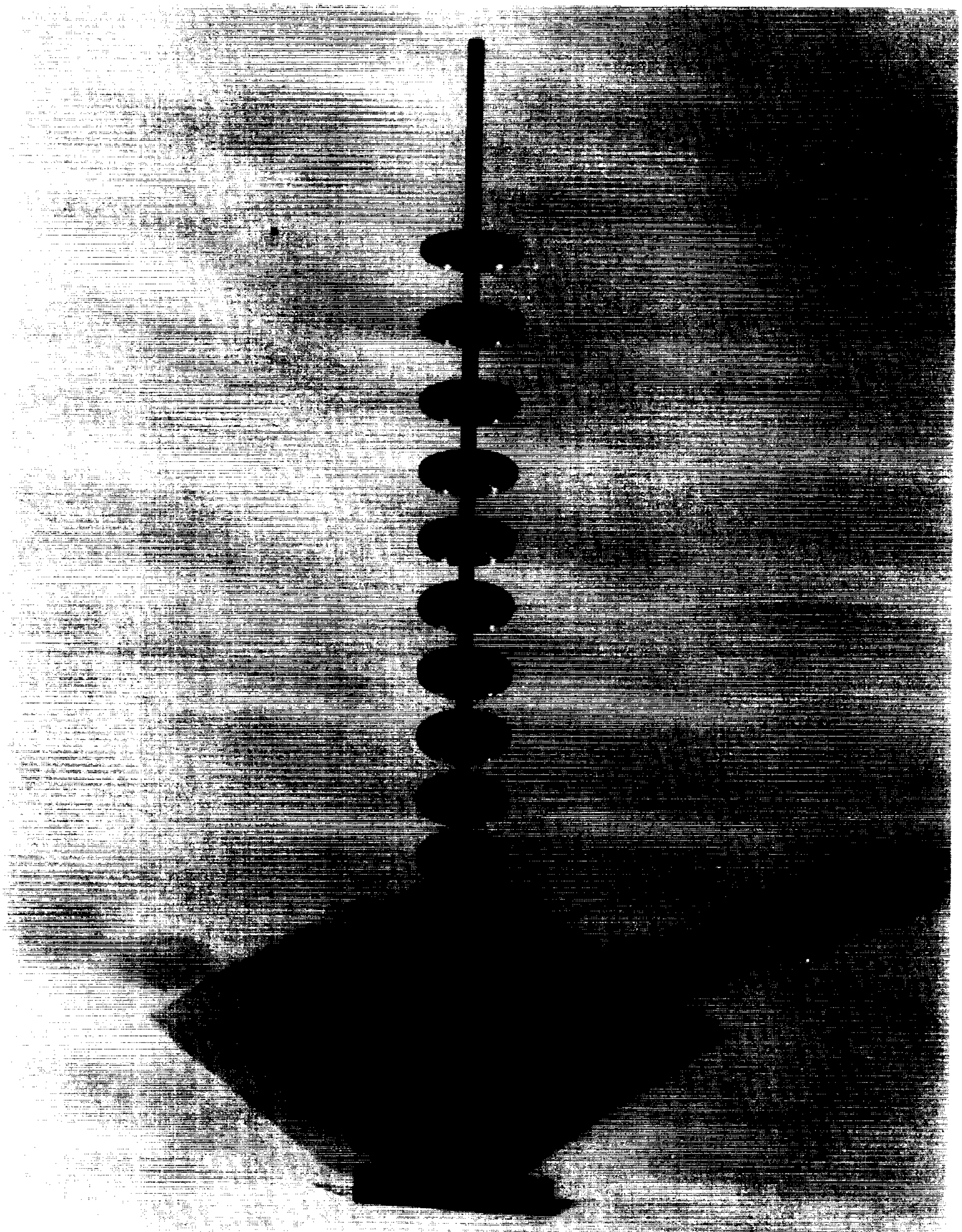
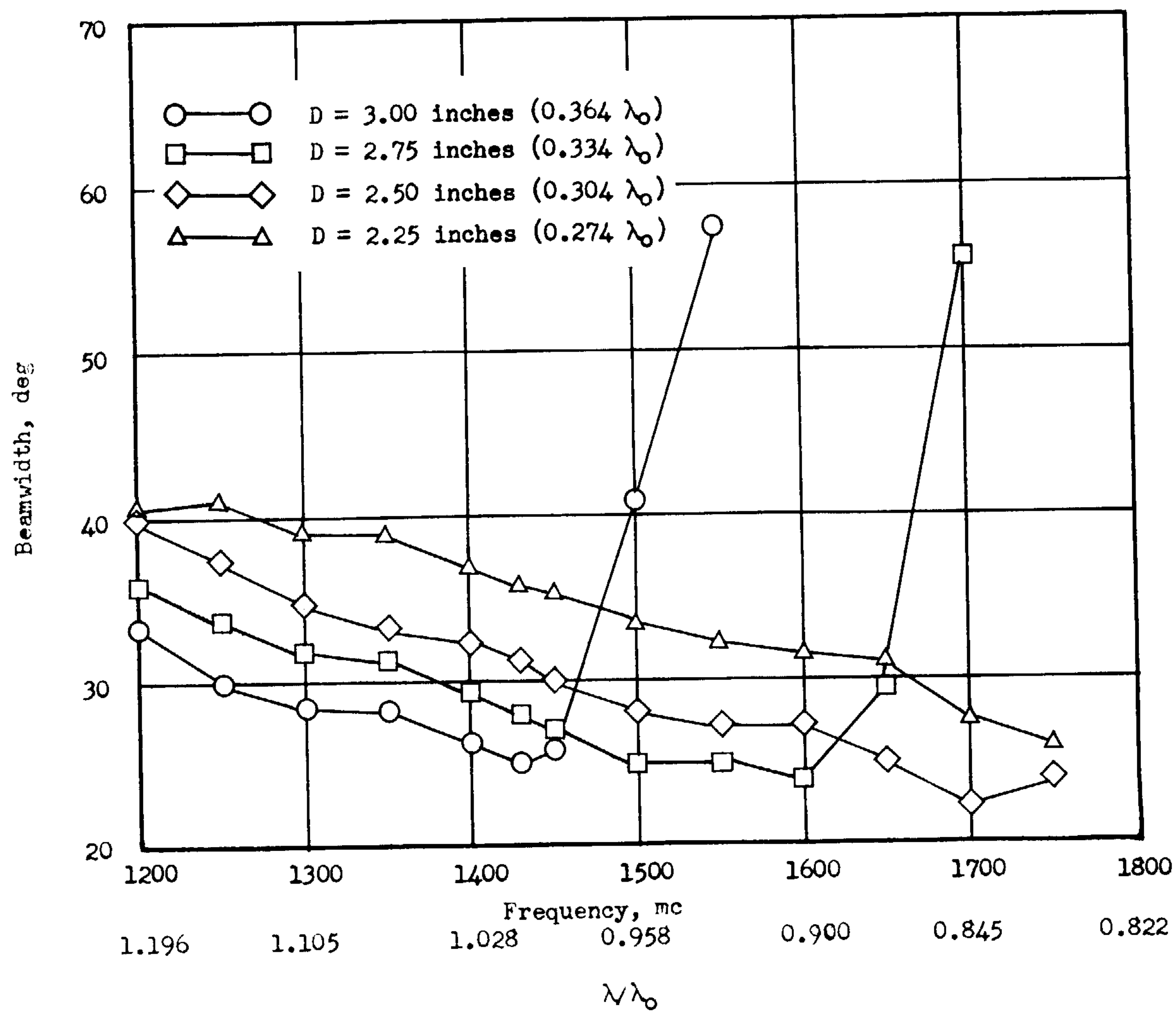
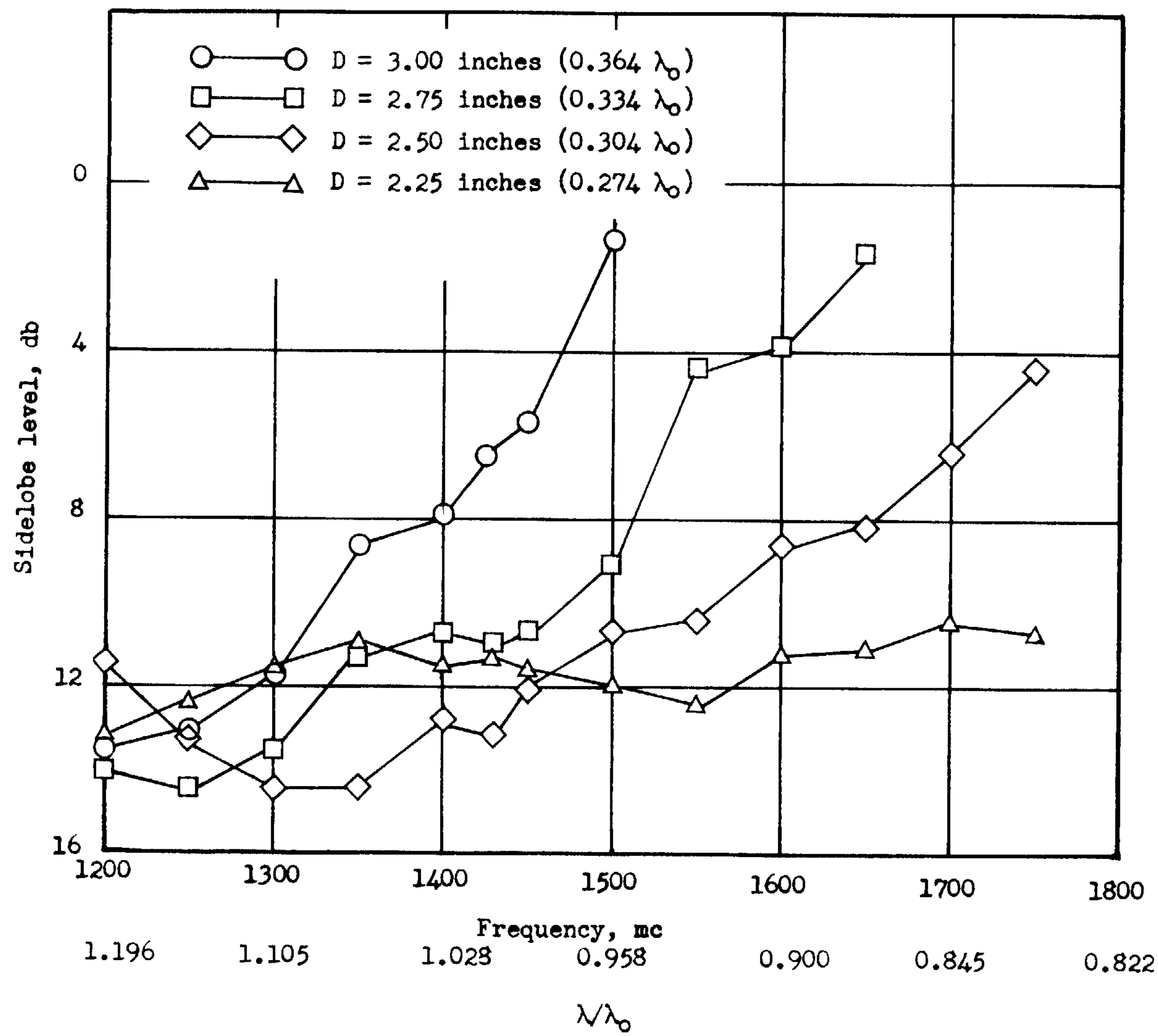


Figure 5.- Rigid Yagi disk element. L-61-5318



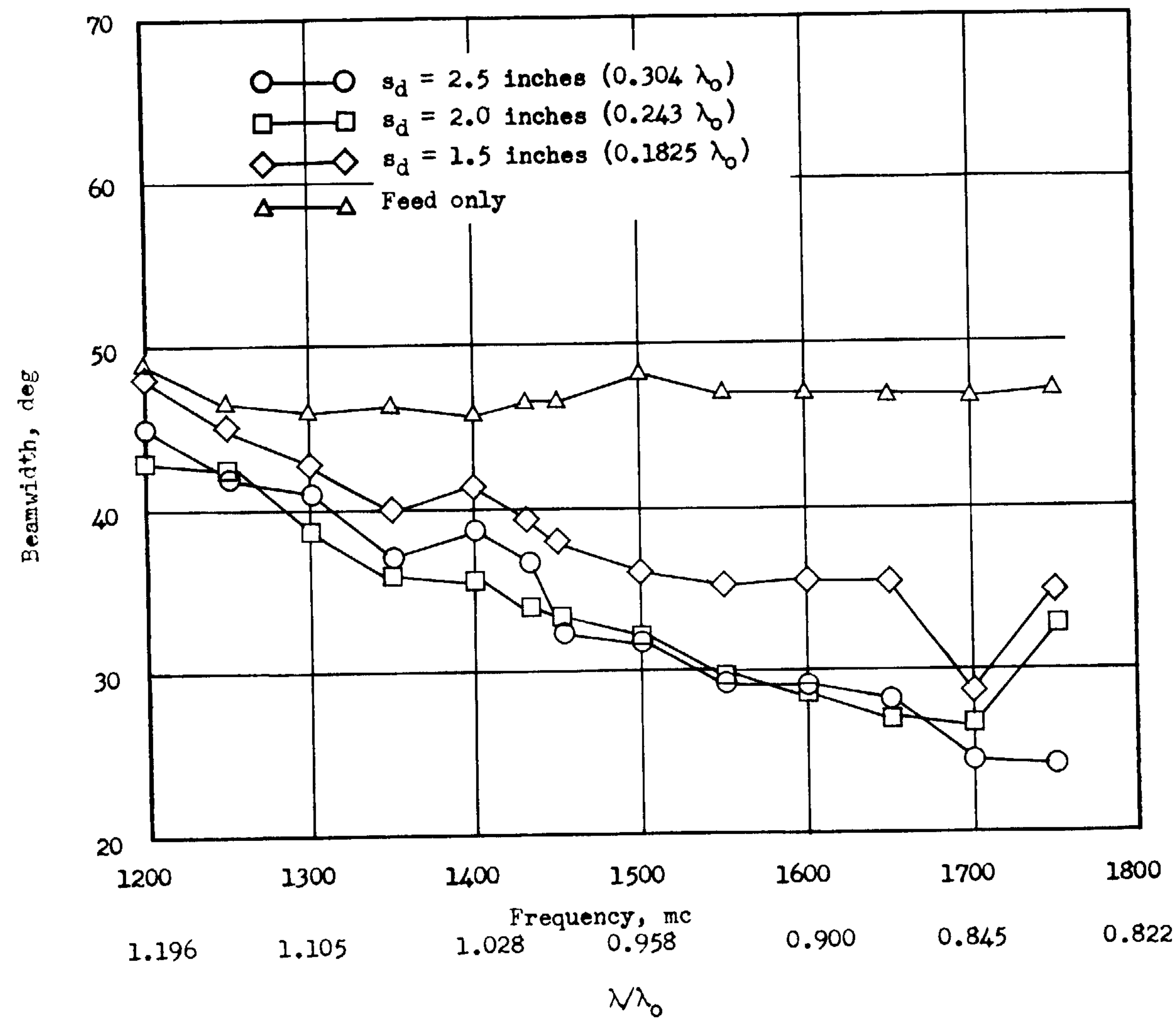
(a) Beamwidth (E and H plane average) as a function of frequency.

Figure 6.- Effect on element characteristics due to changes in disk diameter.



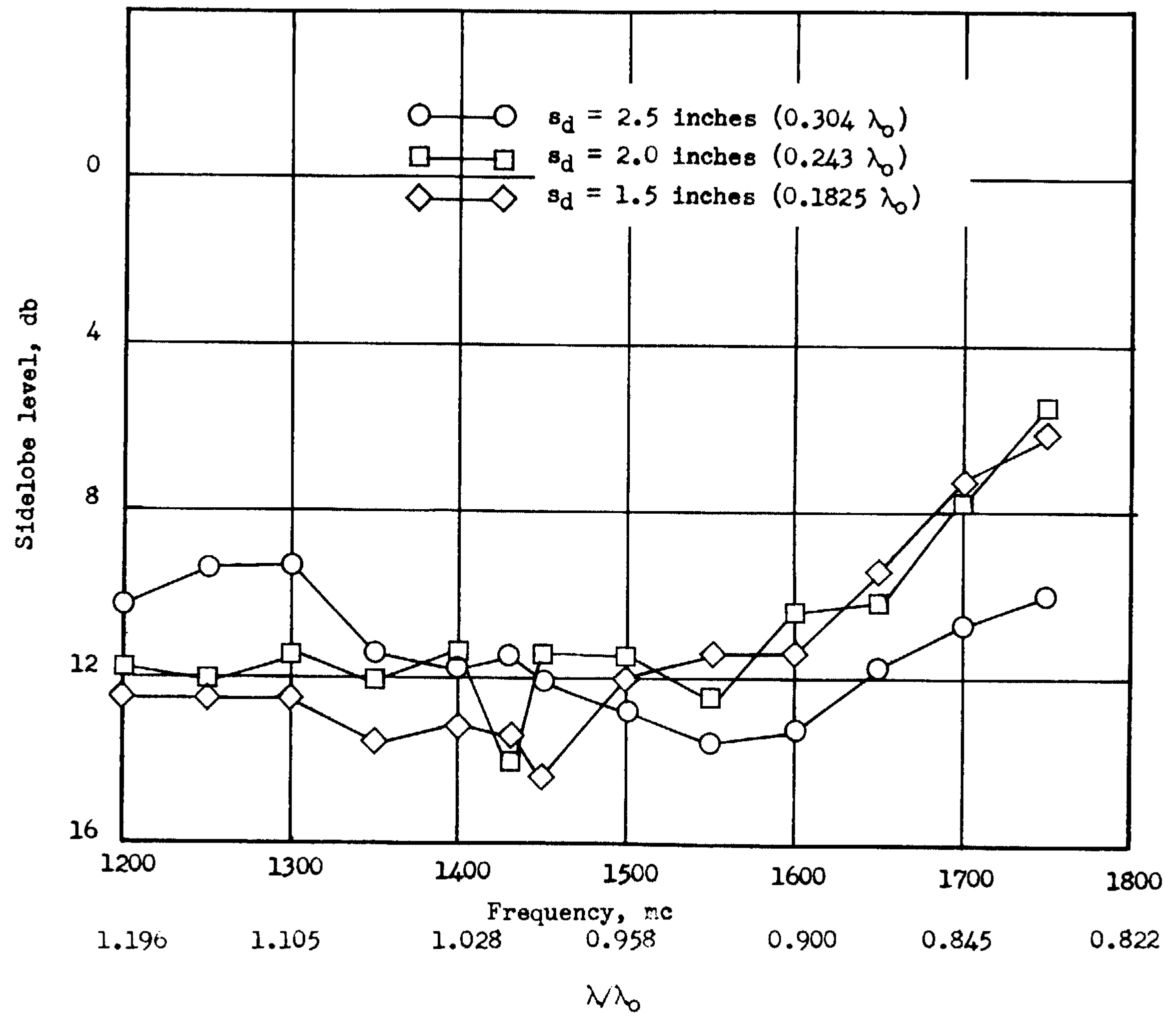
(b) Sidelobe level (maximum value) as a function of frequency.

Figure 6.- Concluded.



(a) Beamwidth (E and H plane average) as a function of frequency.

Figure 7.- Effect on element characteristics due to changes in disk spacing.



(b) Sidelobe level (maximum value) as a function of frequency.

Figure 7.- Concluded.

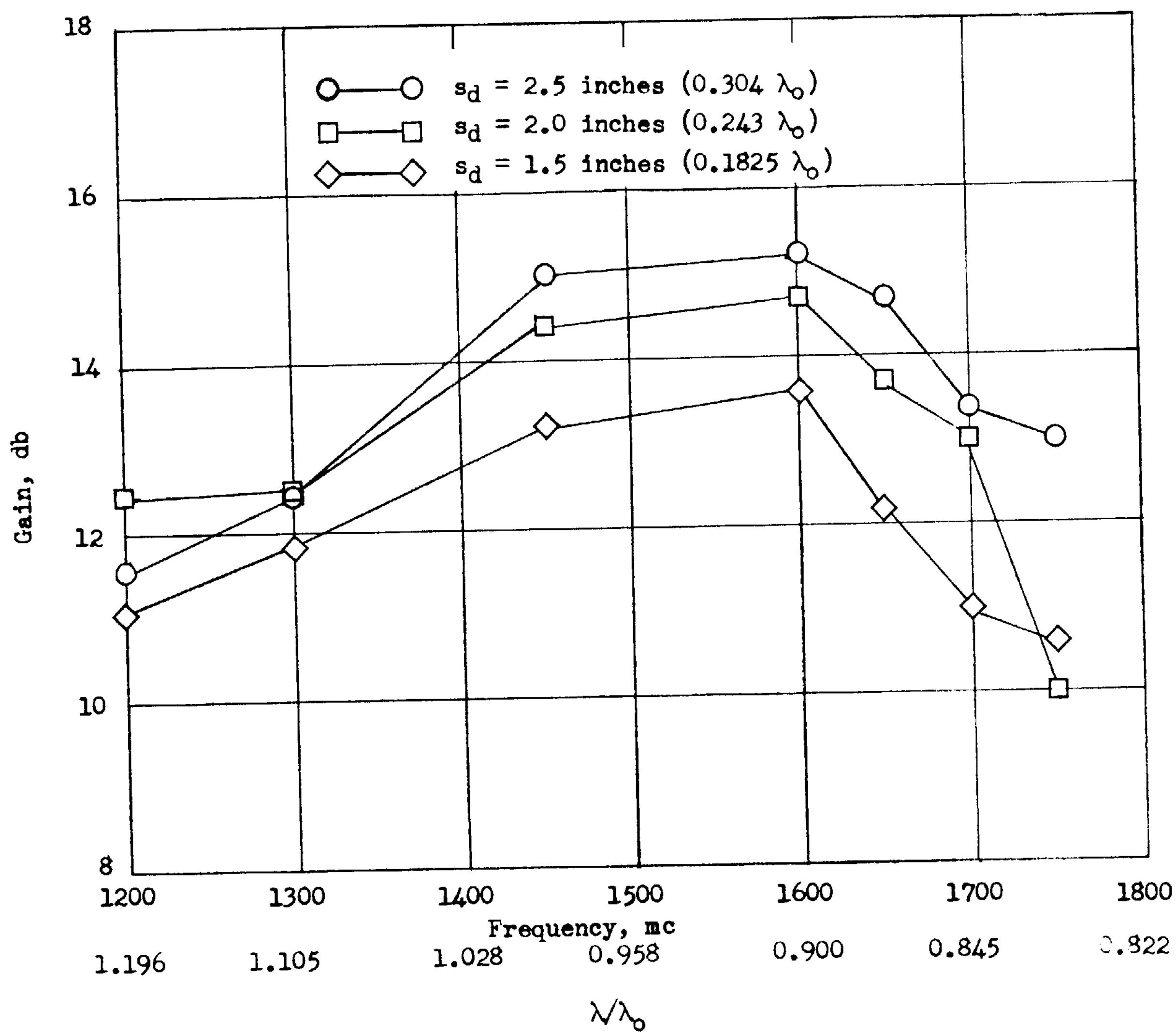
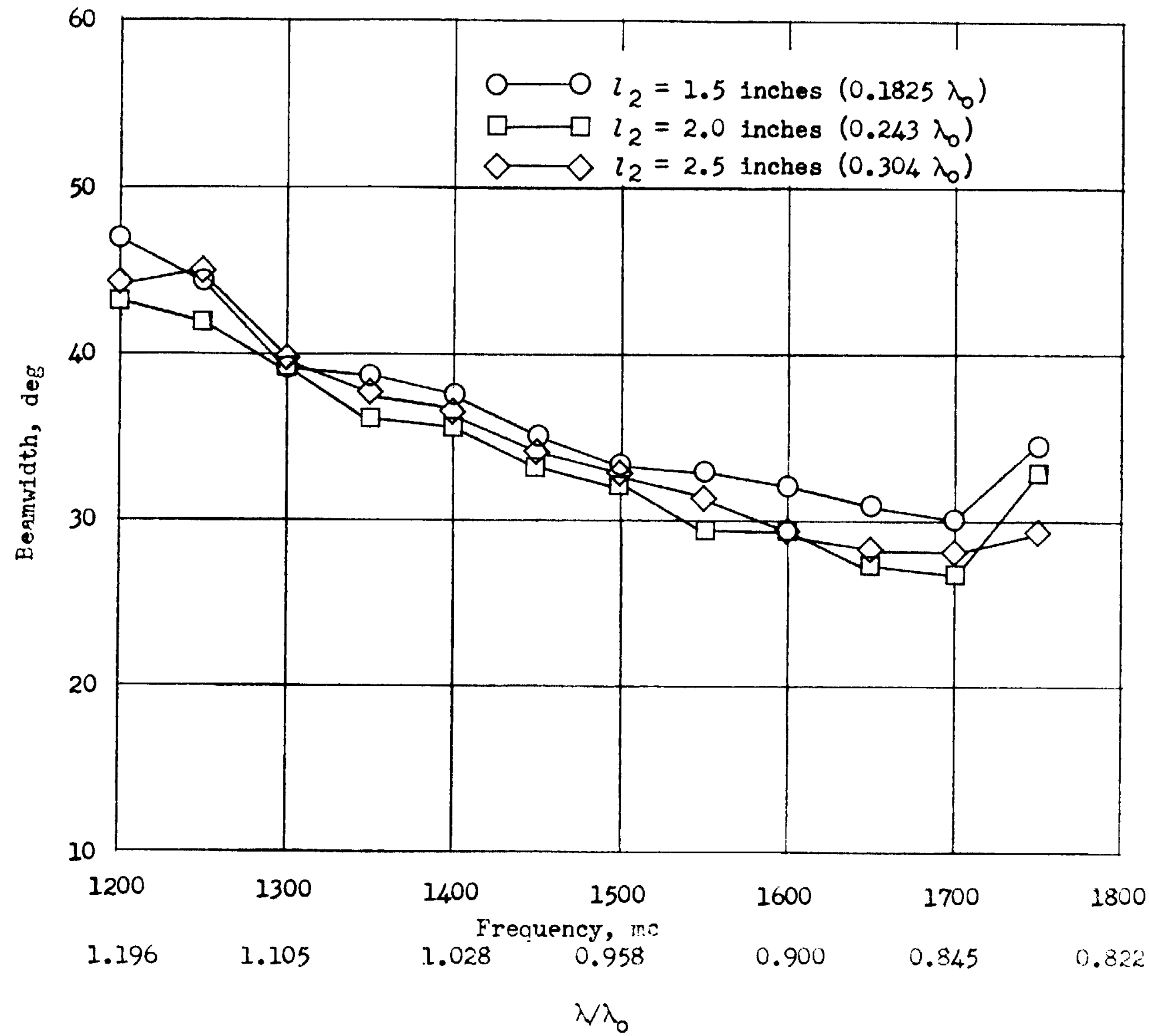
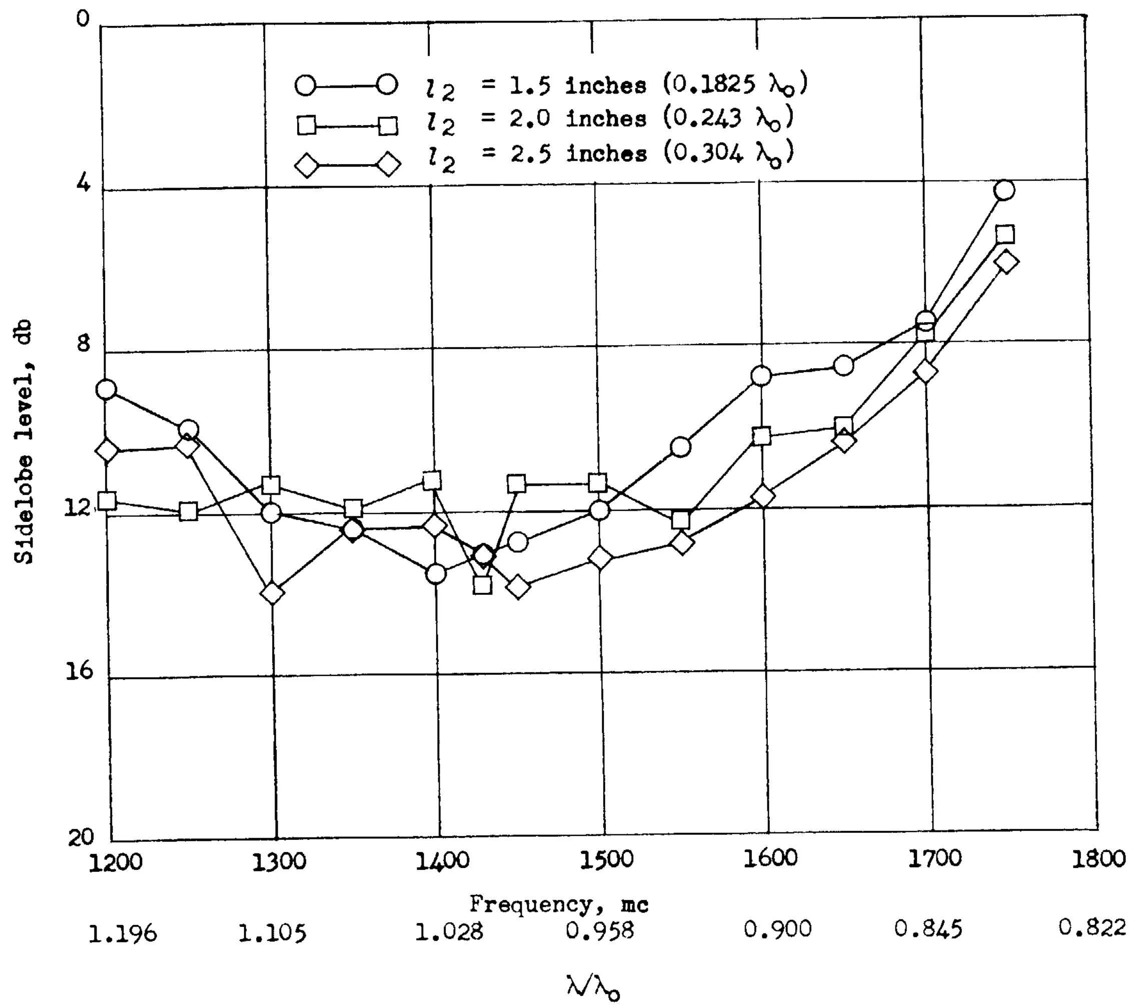


Figure 8.- Element gain as a function of frequency for various disk spacings S.



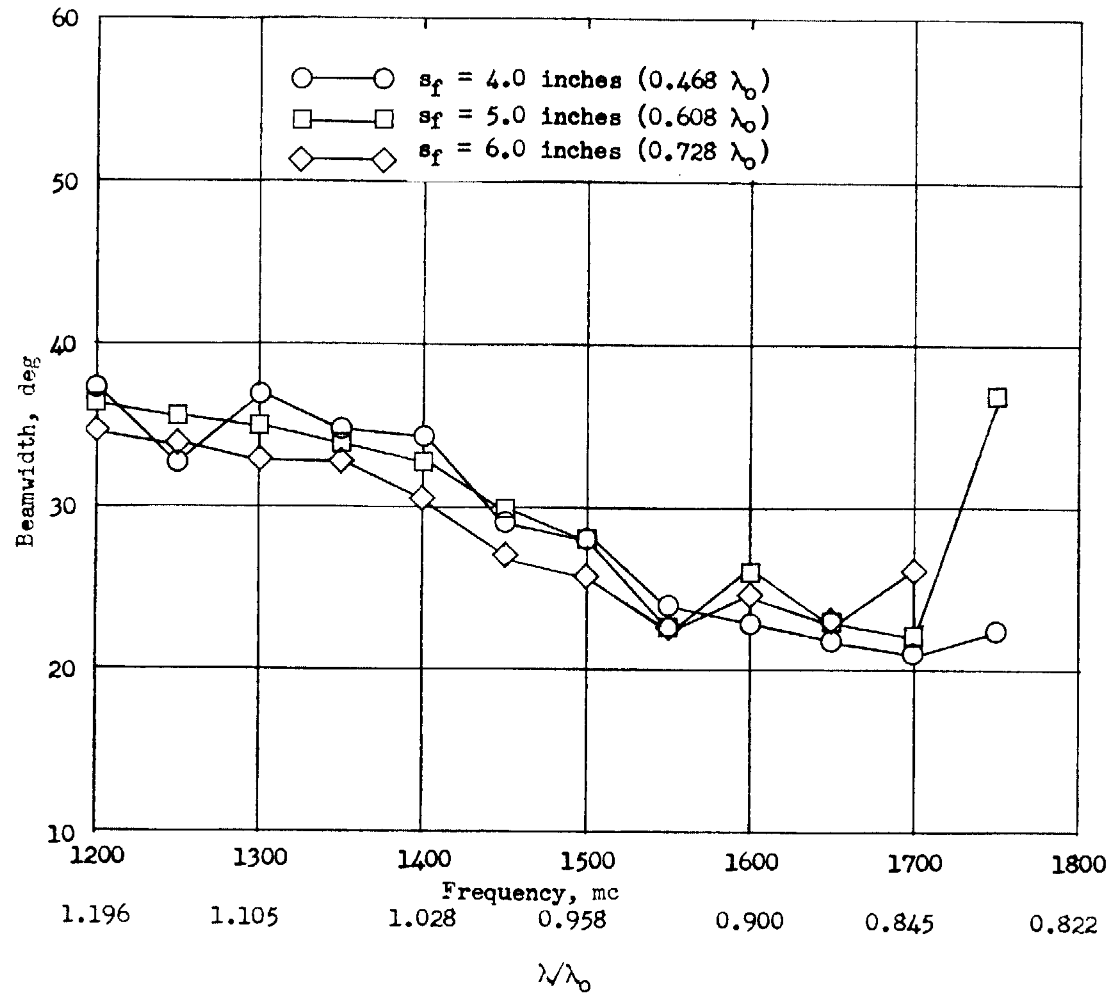
(a) Element beamwidth (E and H plane average) as a function of frequency.

Figure 9.- Effect on element characteristics due to changes in feed to first disk spacing.



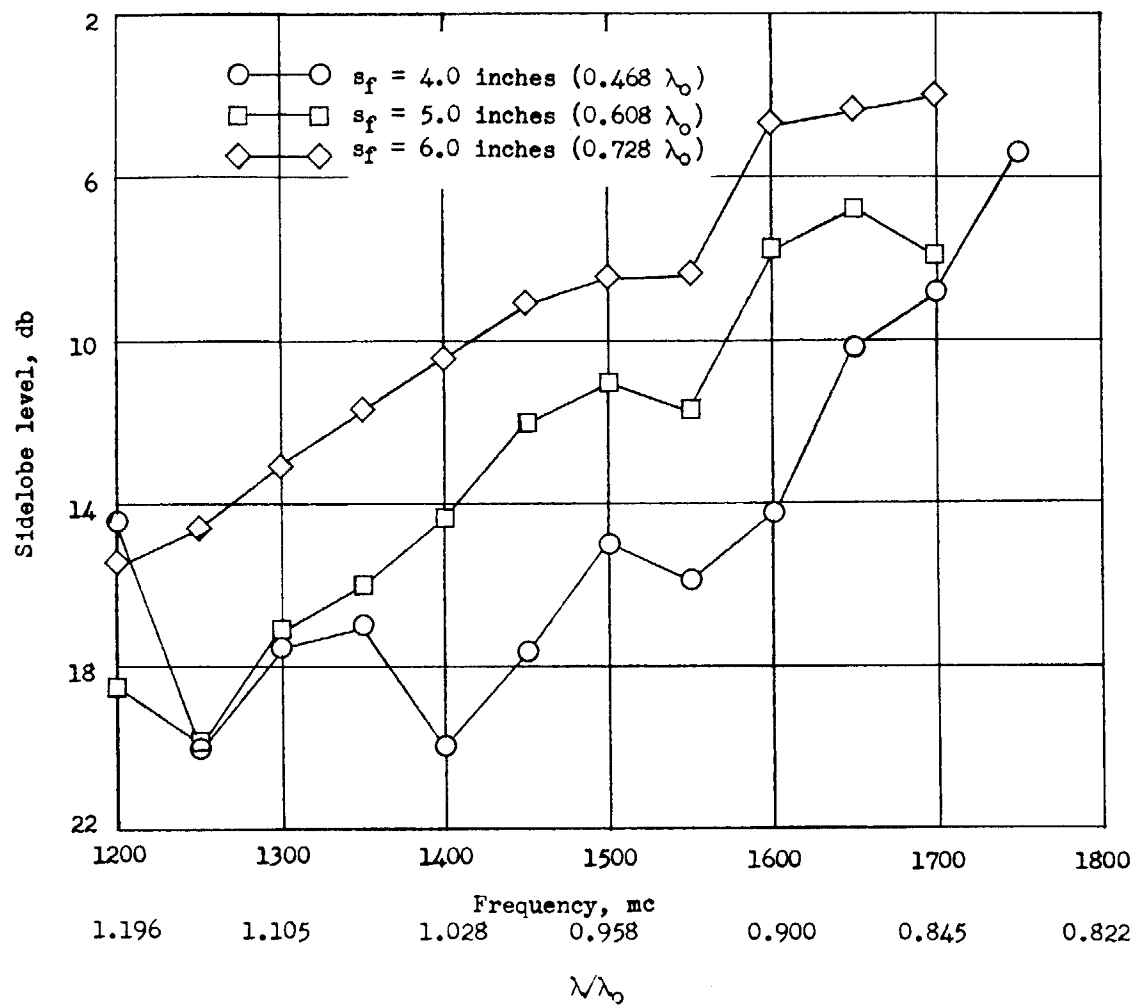
(b) Element sidelobe level (maximum value) as a function of frequency.

Figure 9.- Concluded.



(a) Element beamwidth (E and H plane average) as a function of frequency.

Figure 10.- Effect on element characteristics due to changes in feed dipole spacing.



(b) Element sidelobe level (maximum value) as a function of frequency.

Figure 10.- Concluded.

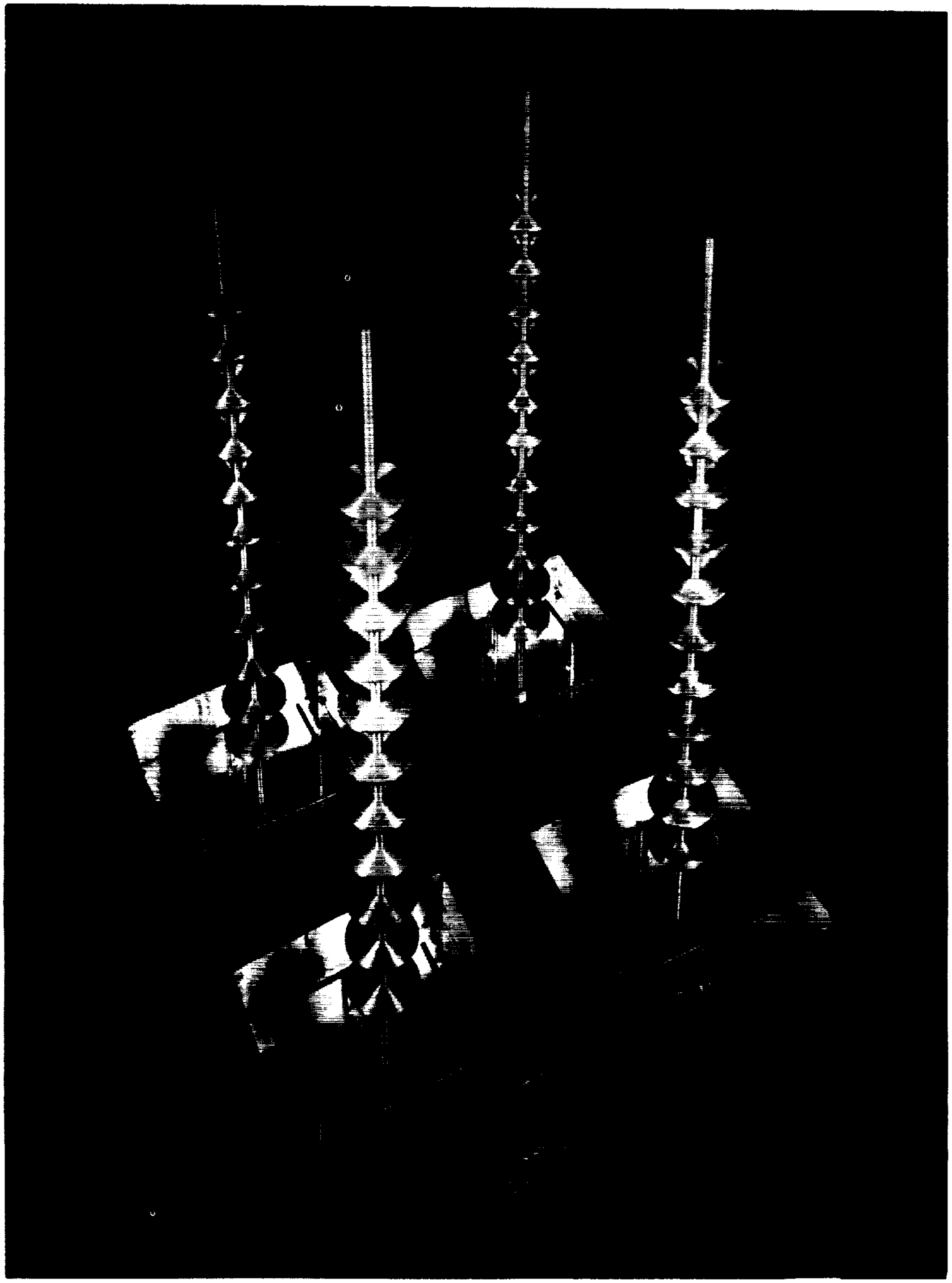
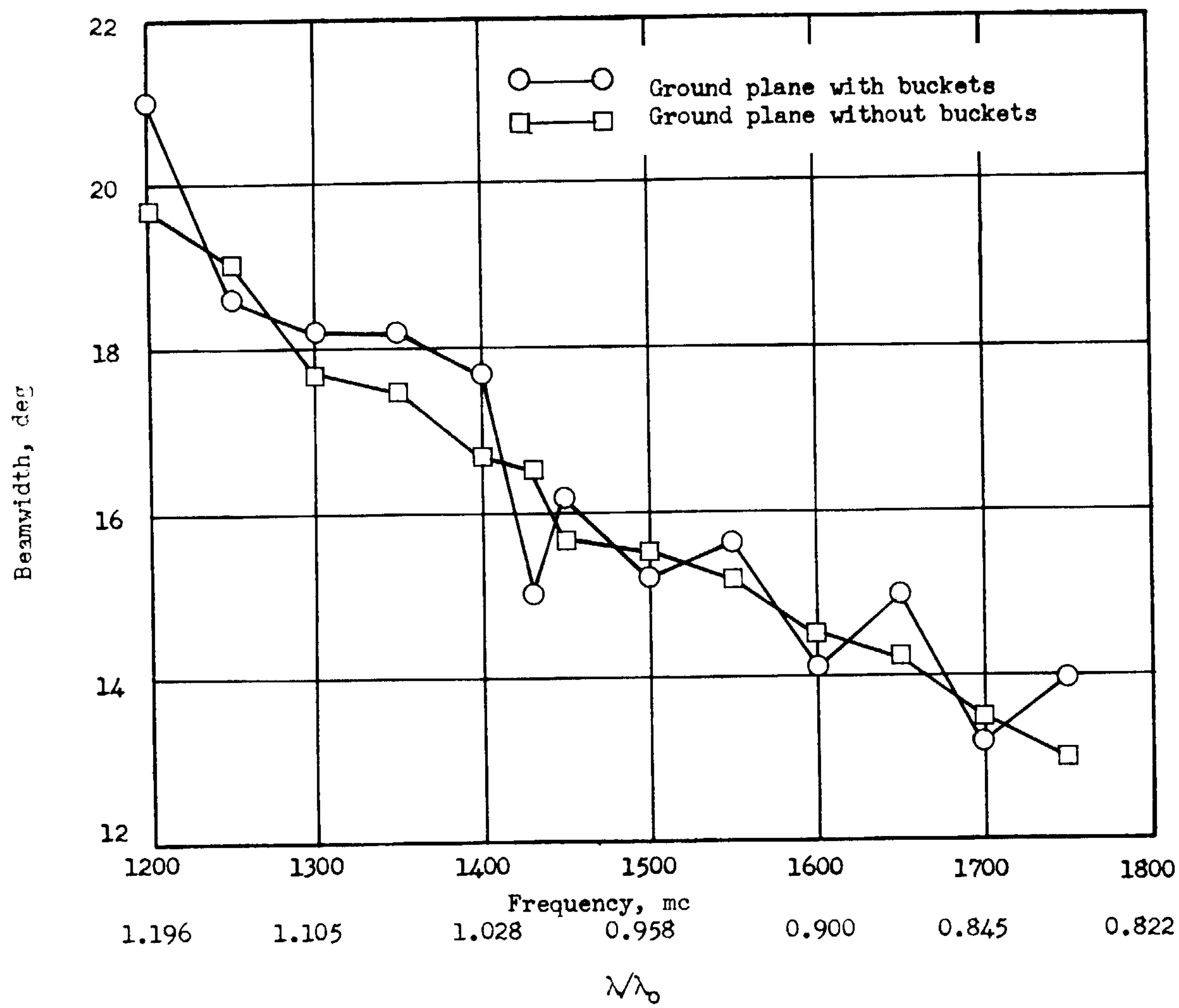
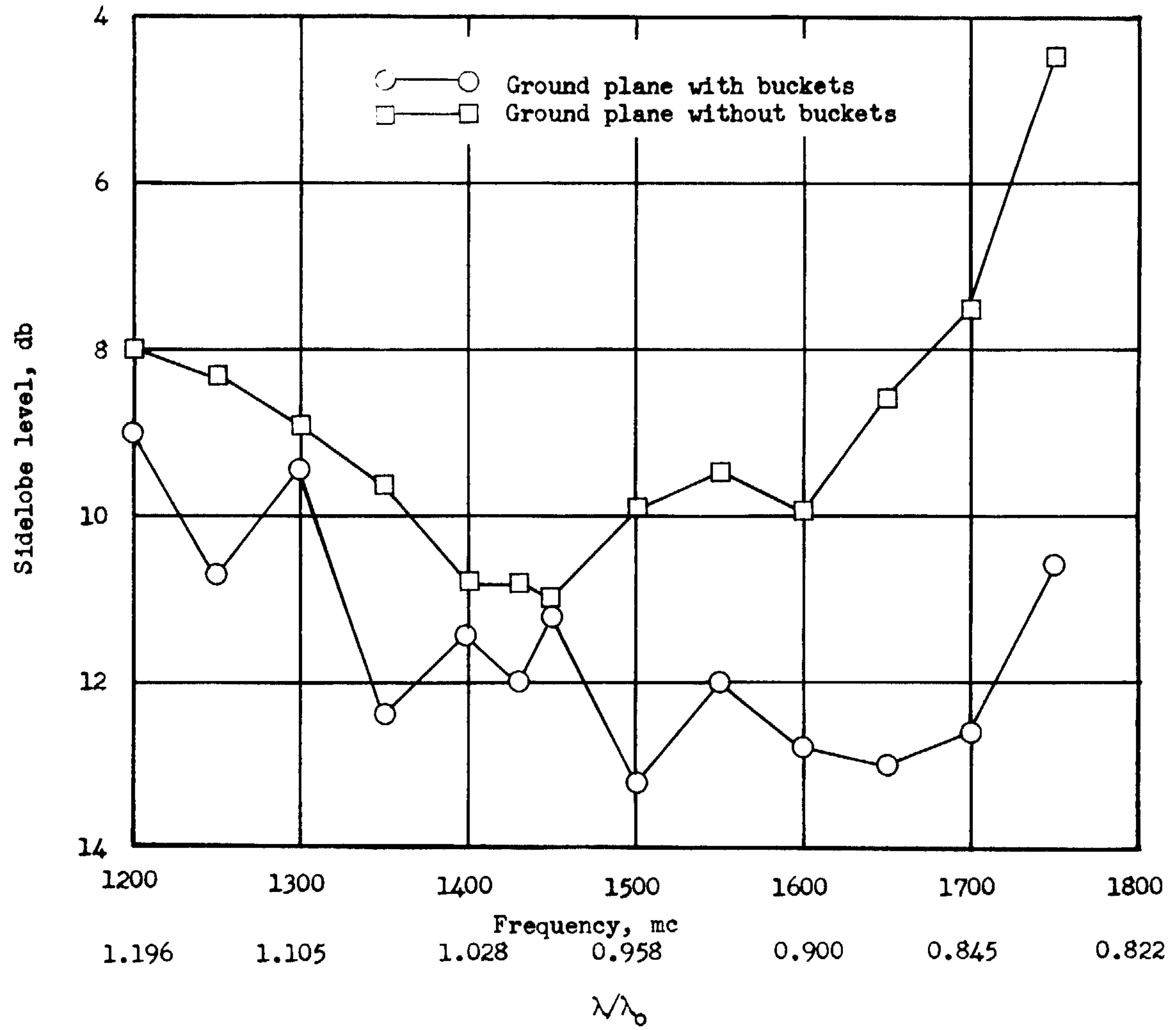


Figure 11.- Array of rigid Yagi disk elements. L-61-4841



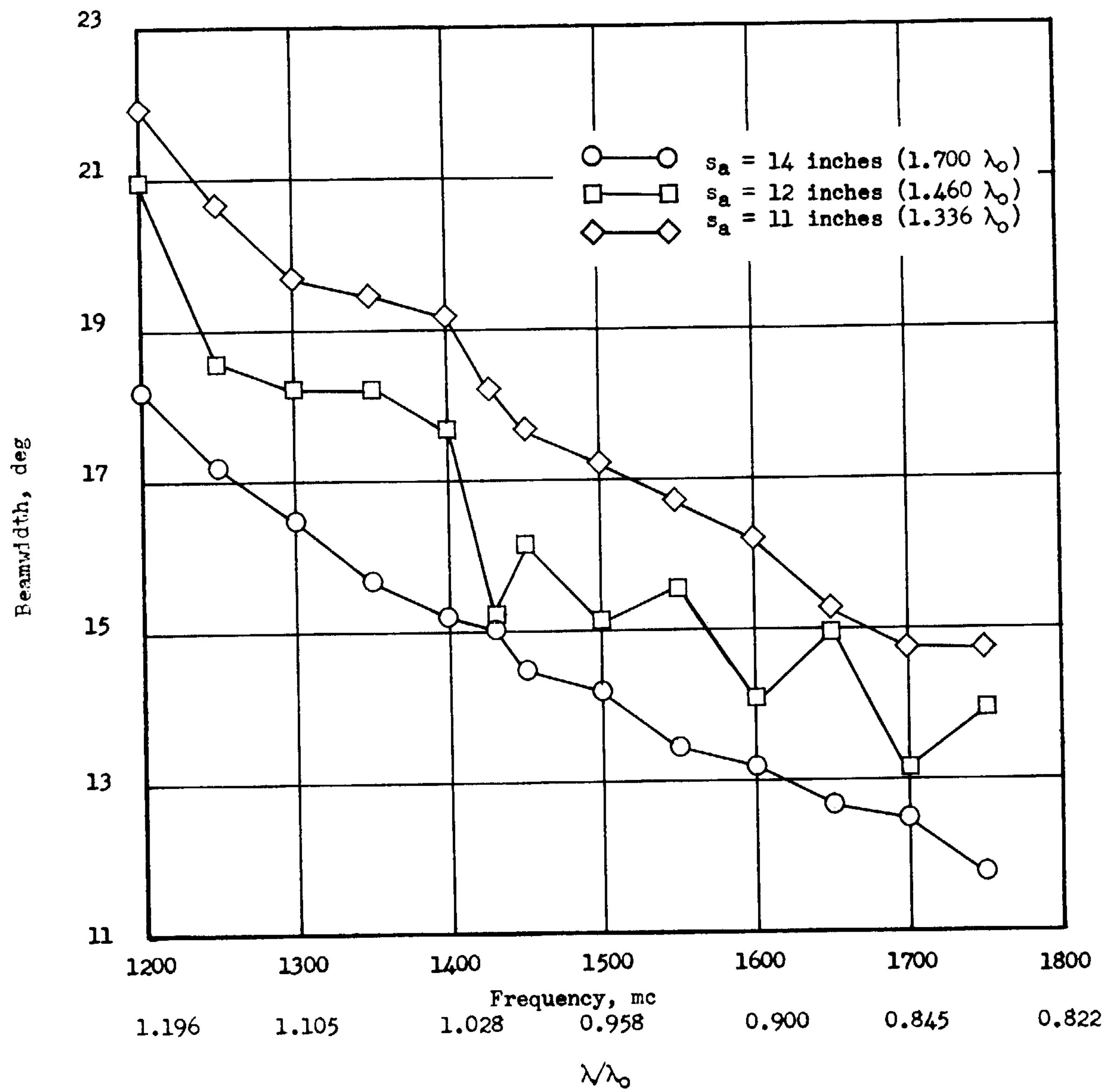
(a) Array beamwidth (E and H plane average) as a function of frequency.

Figure 12.- Effect on array characteristics of feed buckets.



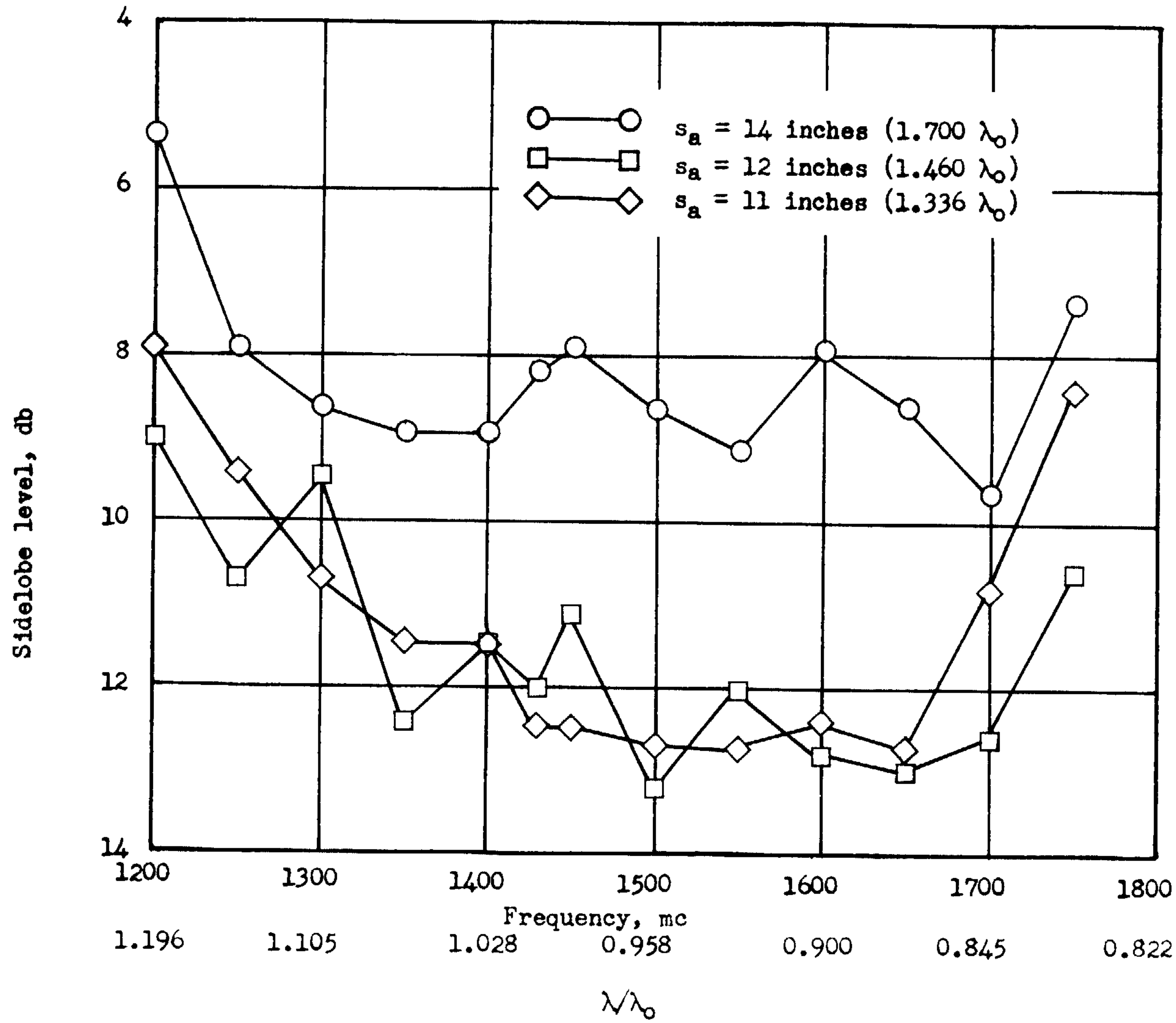
(b) Array sidelobe level (maximum value) as a function of frequency.

Figure 12.- Concluded.



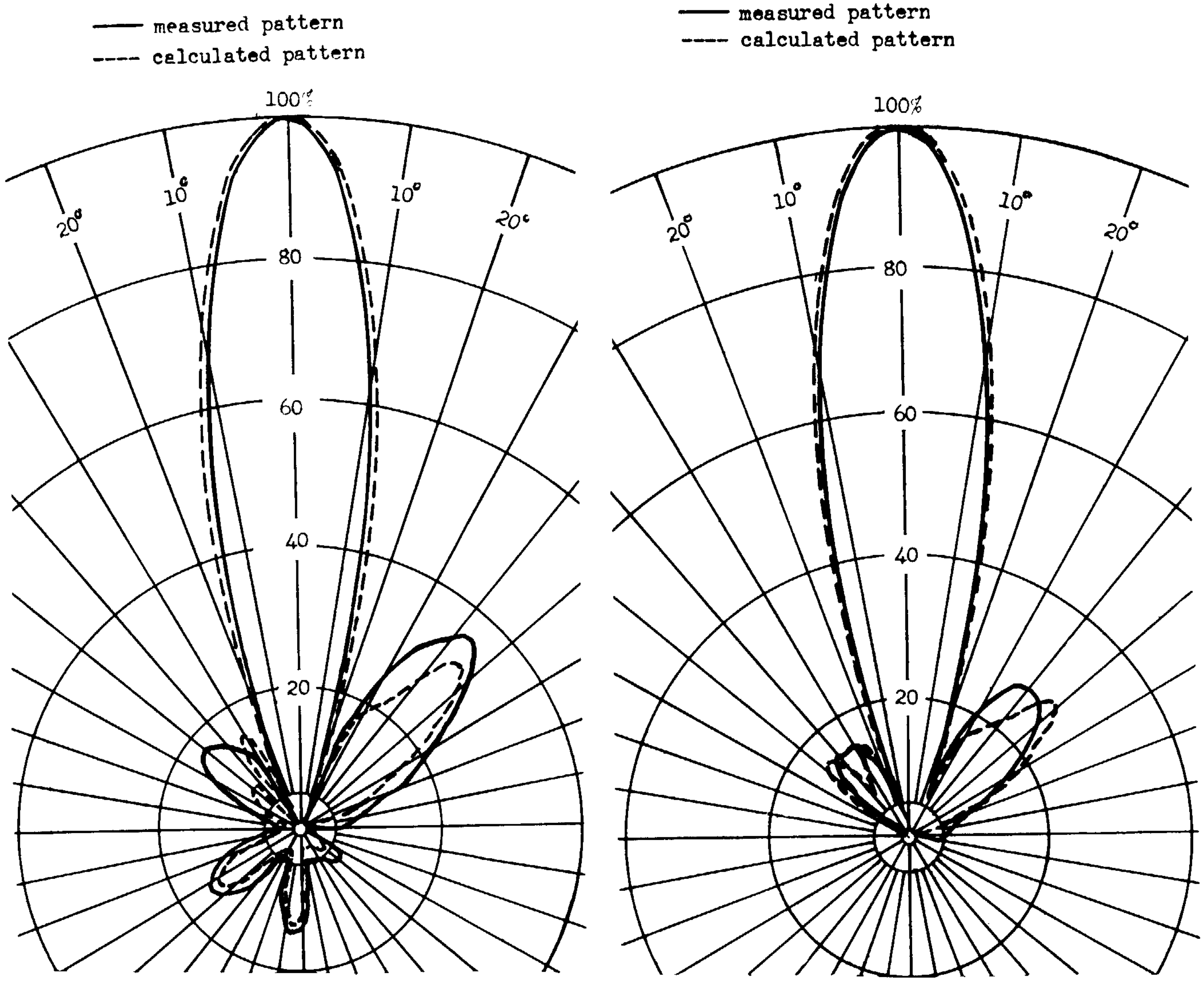
(a) Array beamwidth (E and H plane average) as a function of frequency.

Figure 13.- Effect on array characteristics due to changes in element spacing.



(b) Array sidelobe level (maximum value) as a function of frequency.

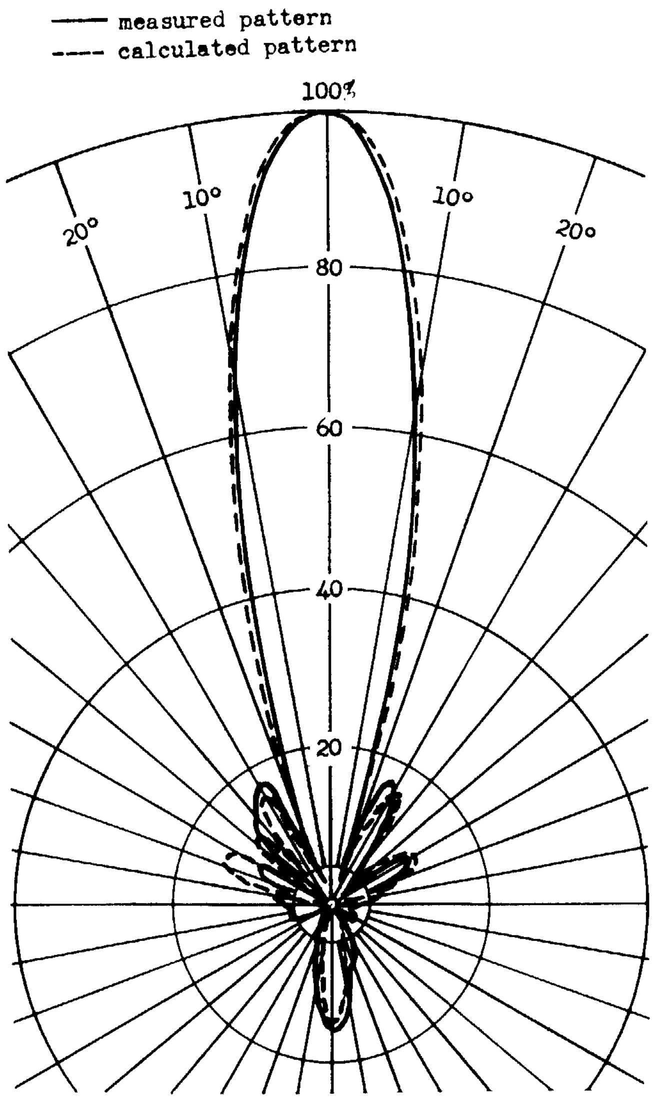
Figure 13.- Concluded.



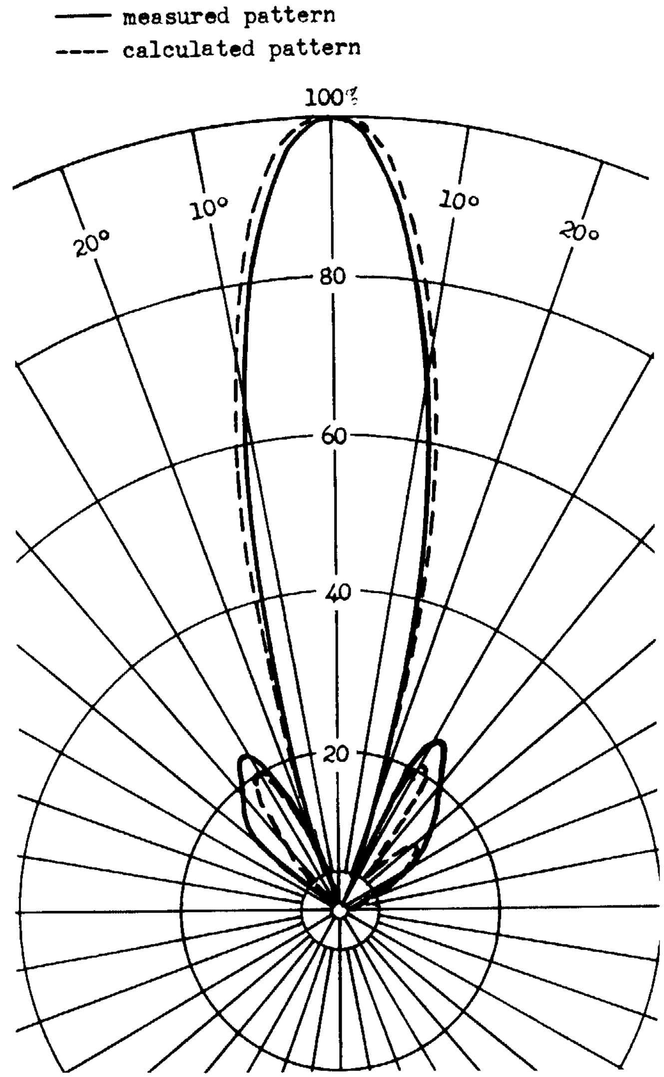
(a) E-plane pattern; f = 1300 mc; without buckets.

(b) E-plane pattern; b = 1300 mc; with buckets.

Figure 14.- Calculated and measured voltage patterns of a four-element array, with element dimensions of table I. s_a = 12 inches.

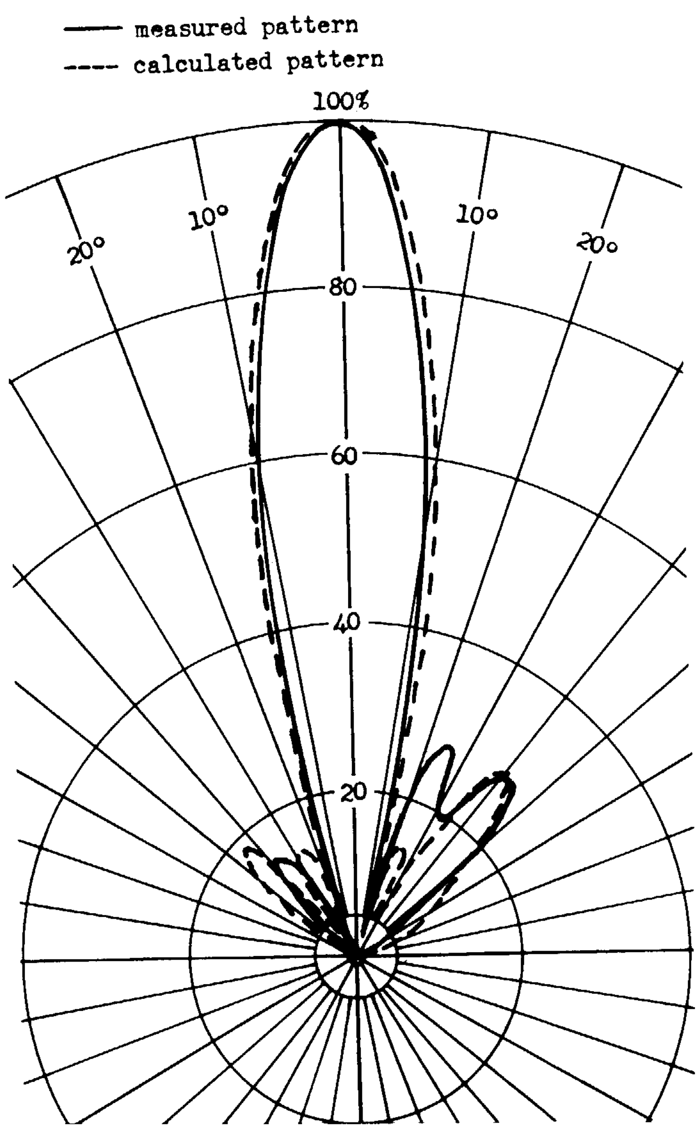


(c) H-plane pattern; f = 1300 mc;
without buckets.

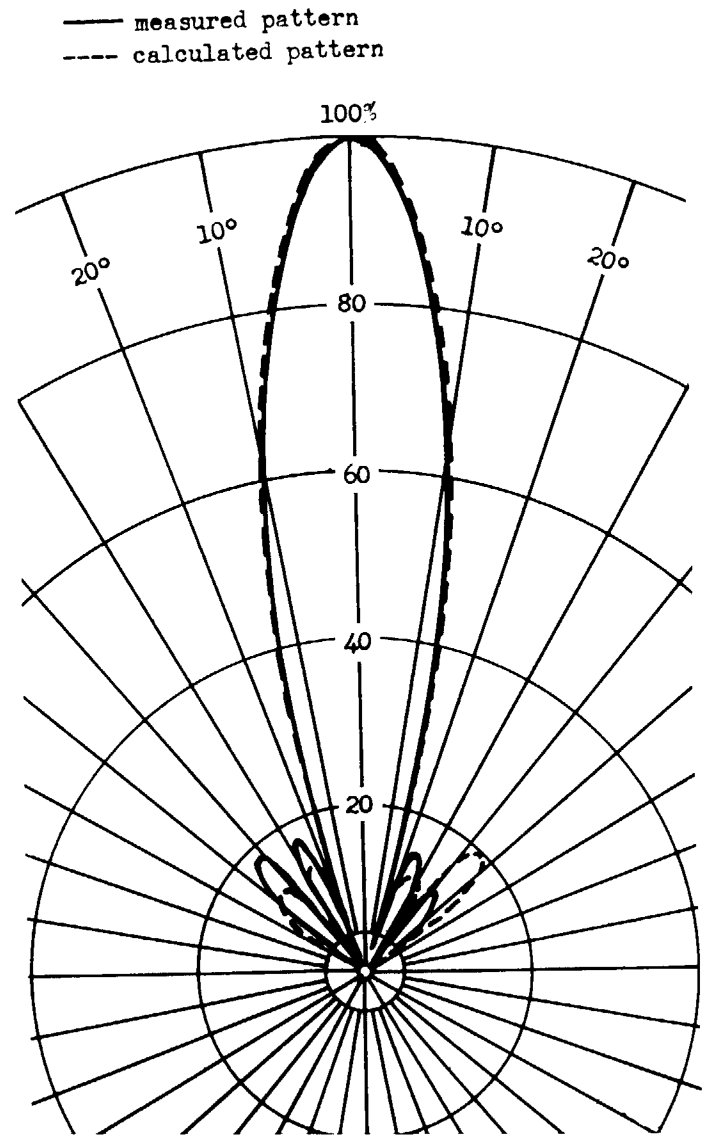


(d) H-plane pattern; f = 1300 mc;
with buckets.

Figure 14.- Continued.

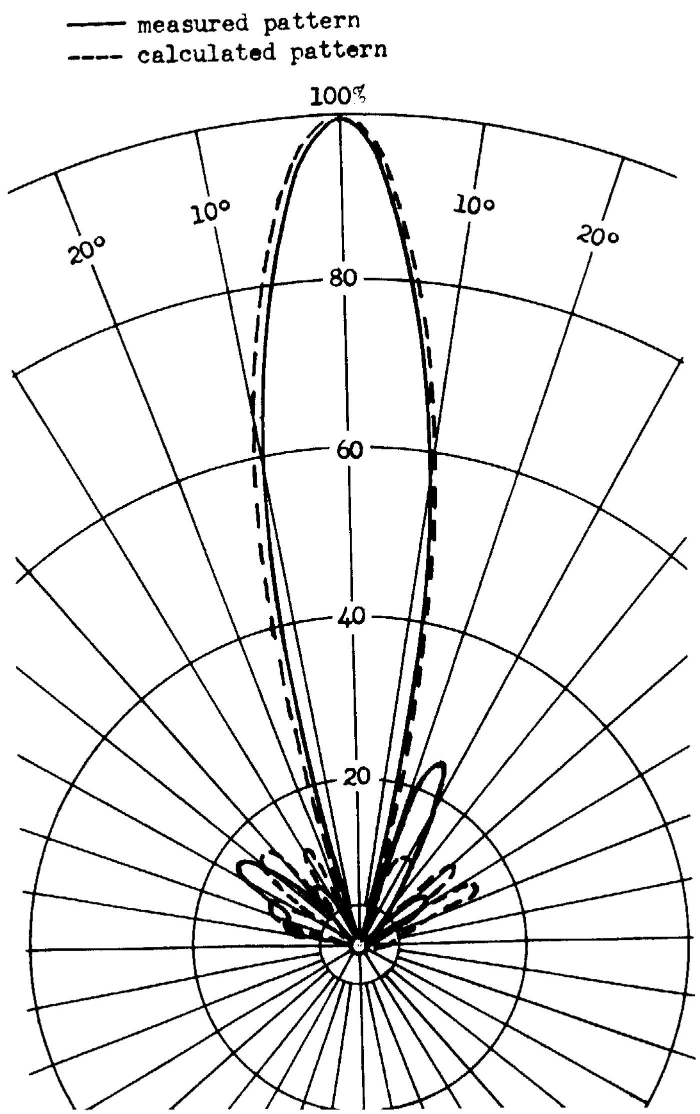


(e) E-plane pattern; f = 1450 mc; without buckets.

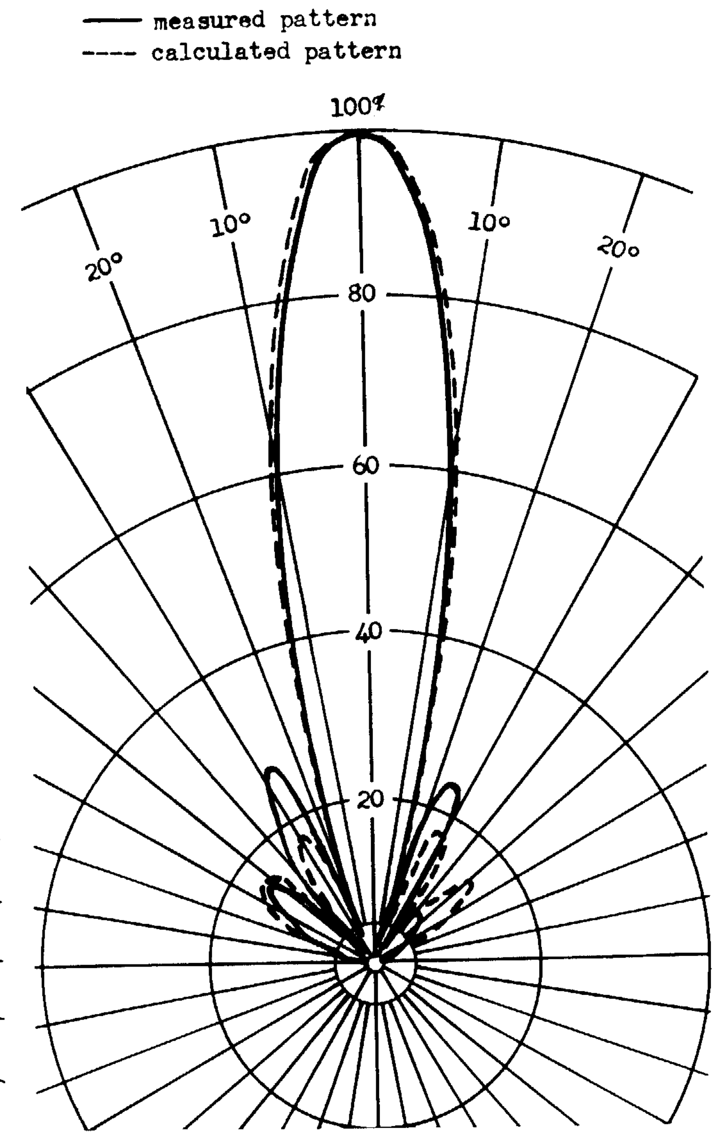


(f) E-plane pattern; f = 1450 mc; with buckets.

Figure 14.- Continued.

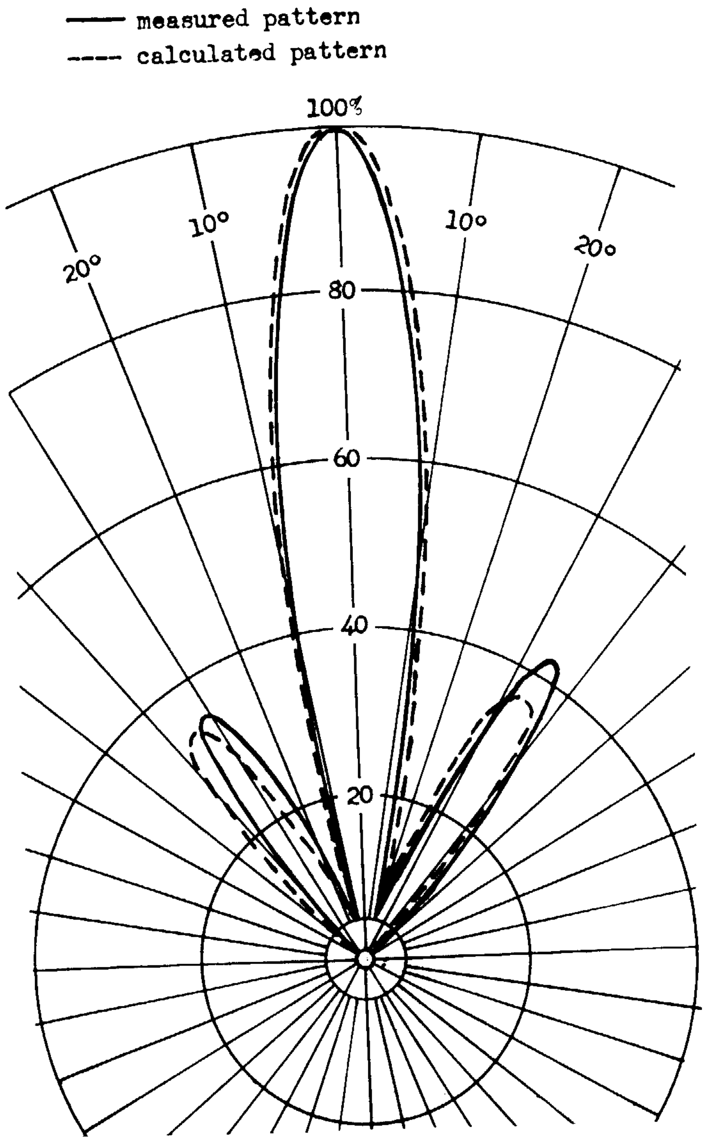


(g) H-plane pattern; f = 1450 mc;
without buckets.

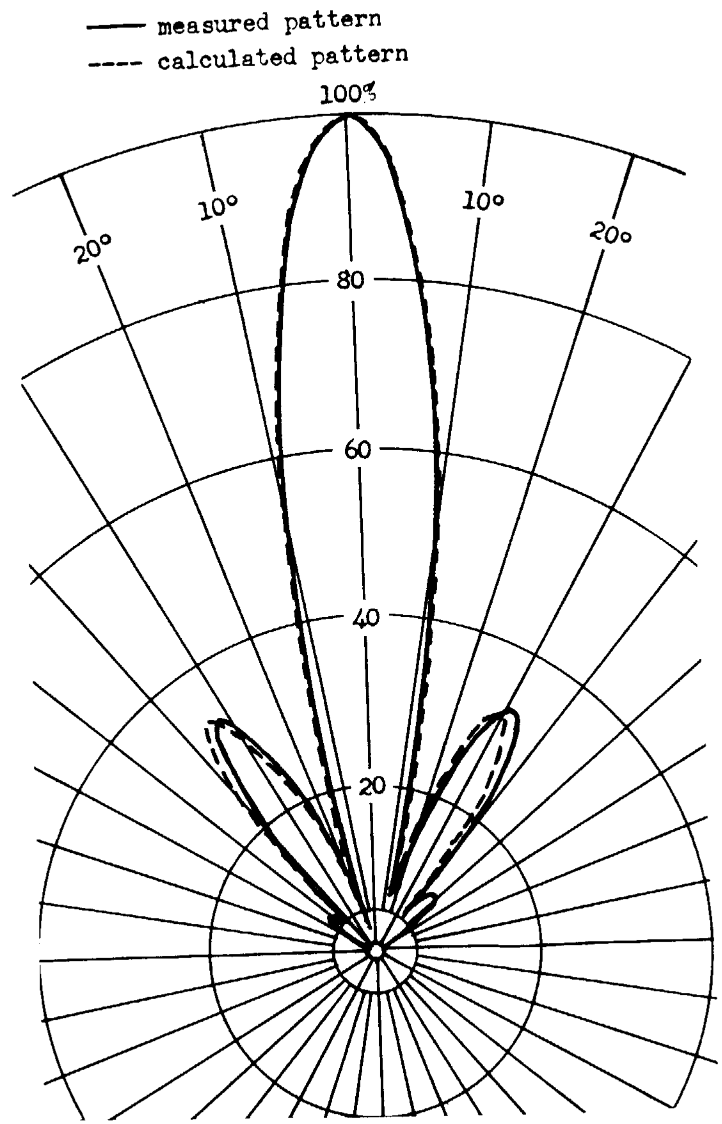


(h) H-plane pattern; f = 1450 mc;
with buckets.

Figure 14.- Continued.

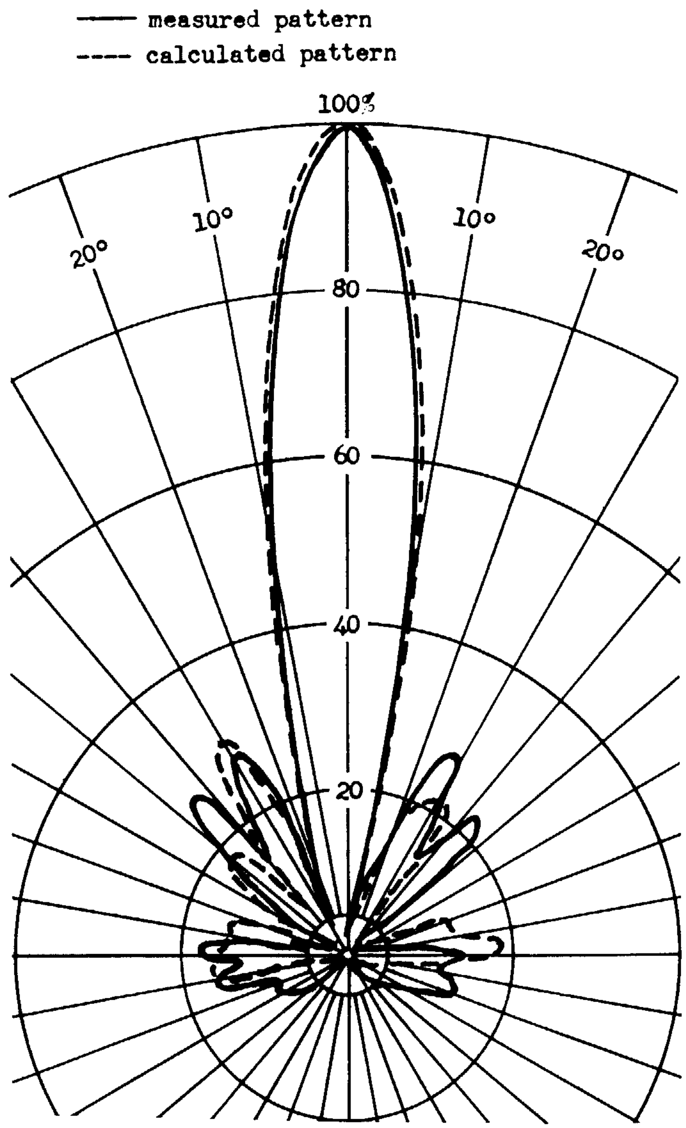


(i) E-plane pattern; f = 1700 mc; without buckets.

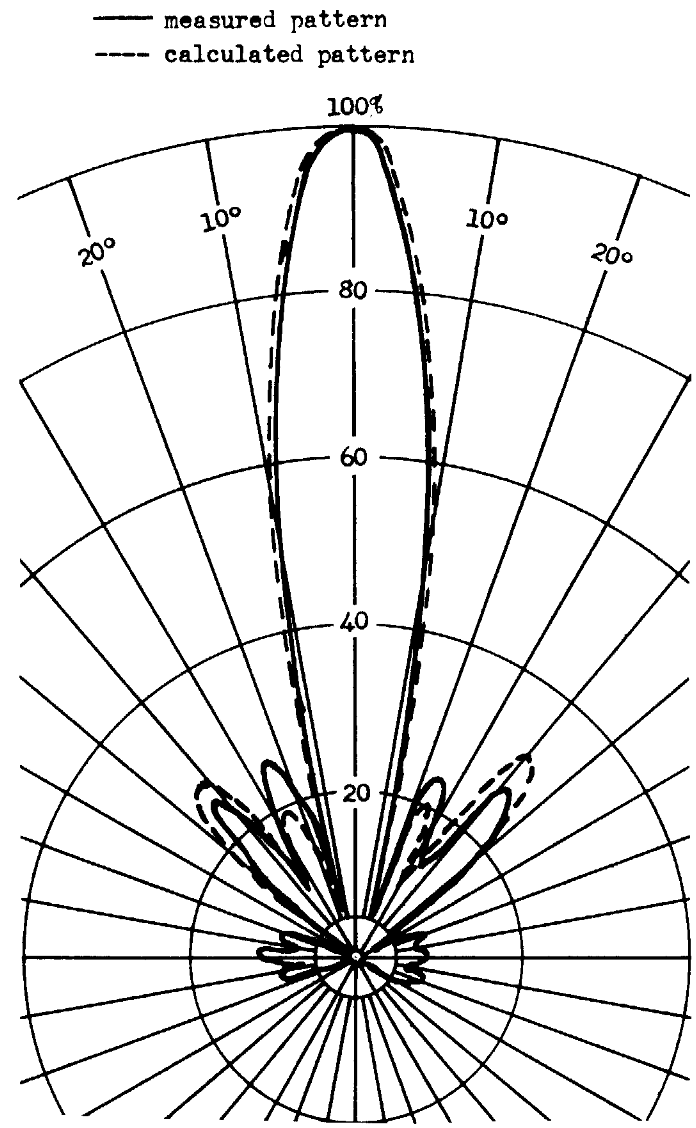


(j) E-plane pattern; f = 1700 mc; with buckets.

Figure 14.- Continued.

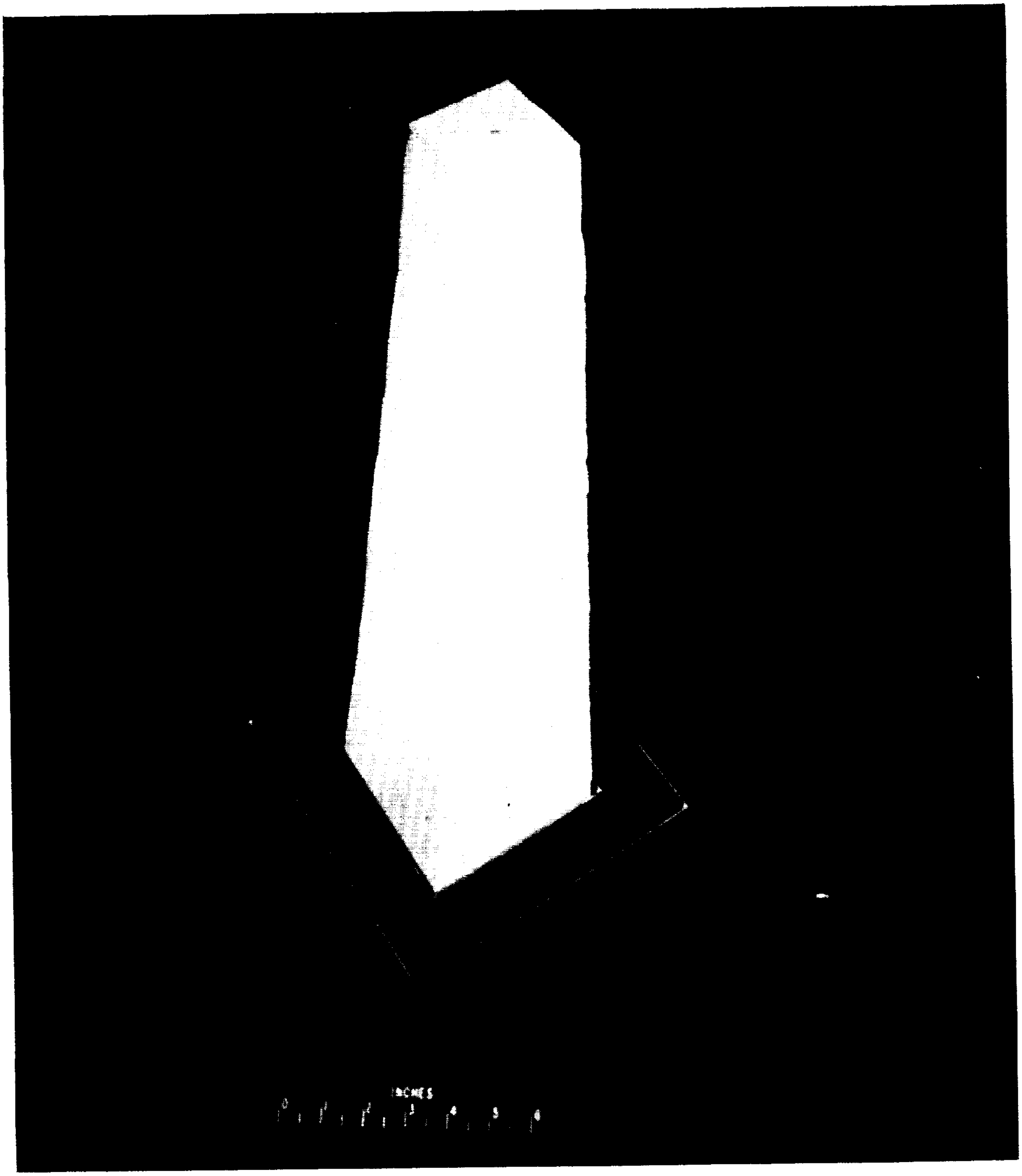


(k) H-plane pattern; f = 1700 mc;
without buckets.



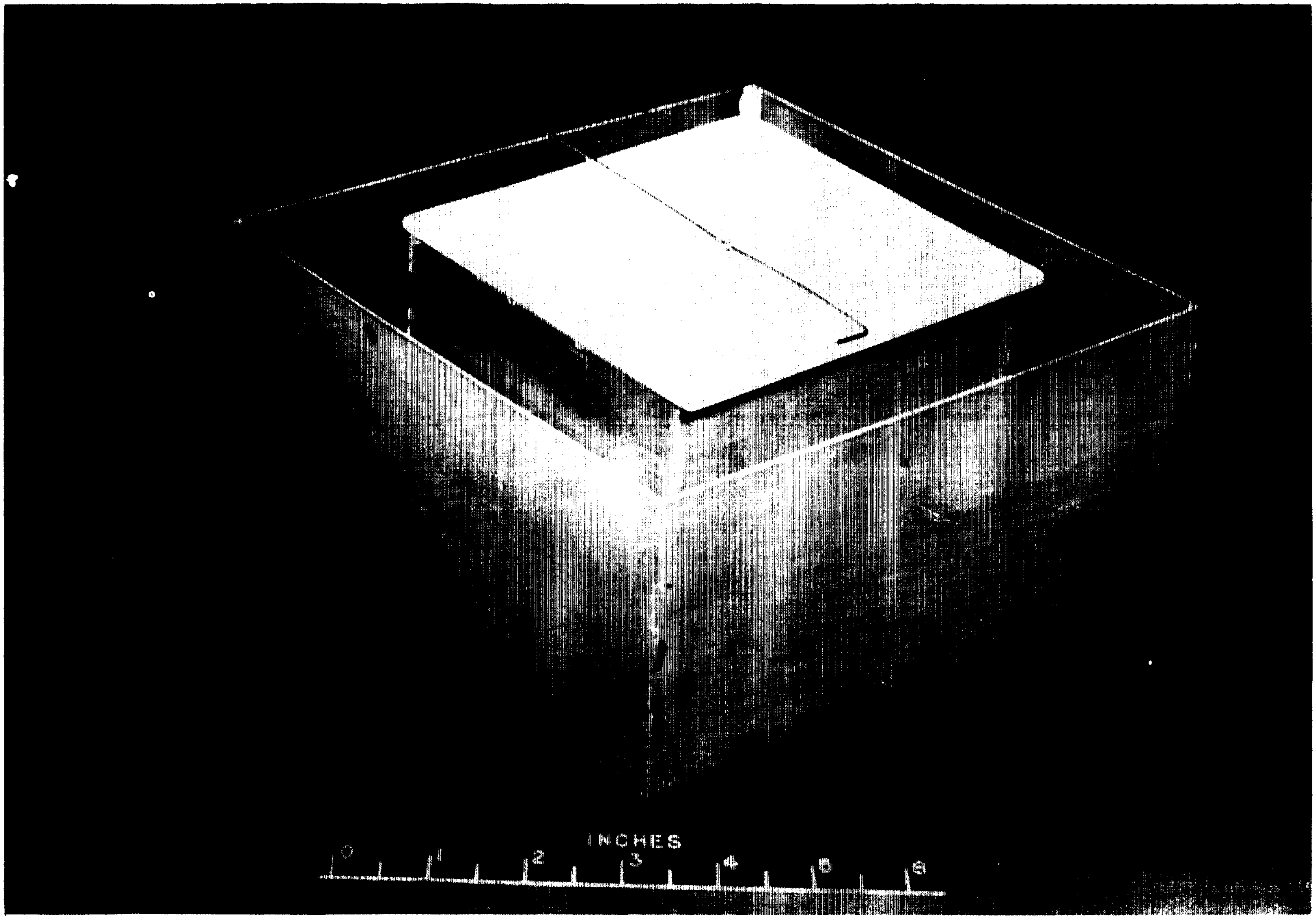
(l) H-plane pattern; f = 1700 mc;
with buckets.

Figure 14.- Concluded.



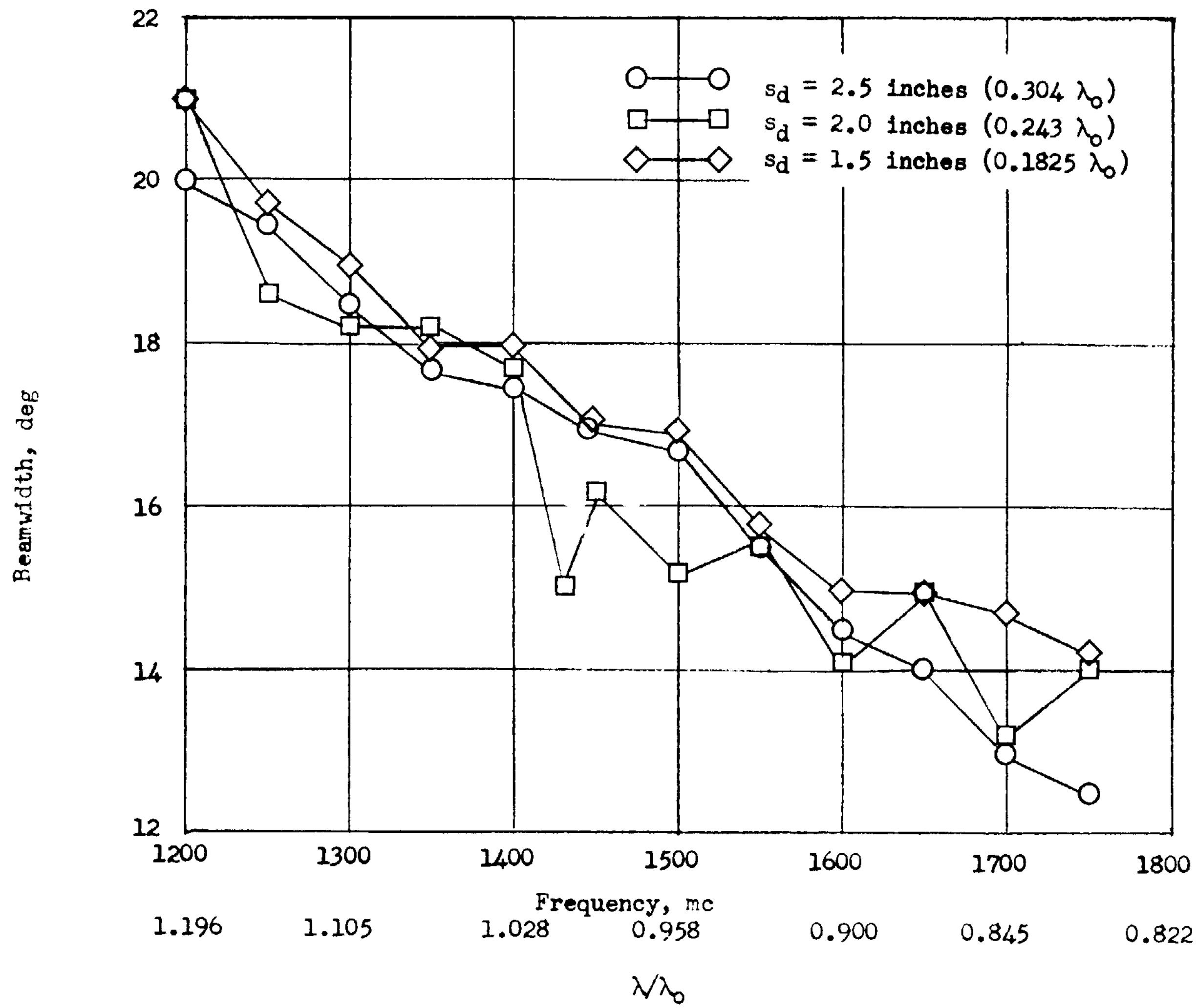
(a) Erected. L-61-4833

Figure 15.- Pyramidal erectable element.



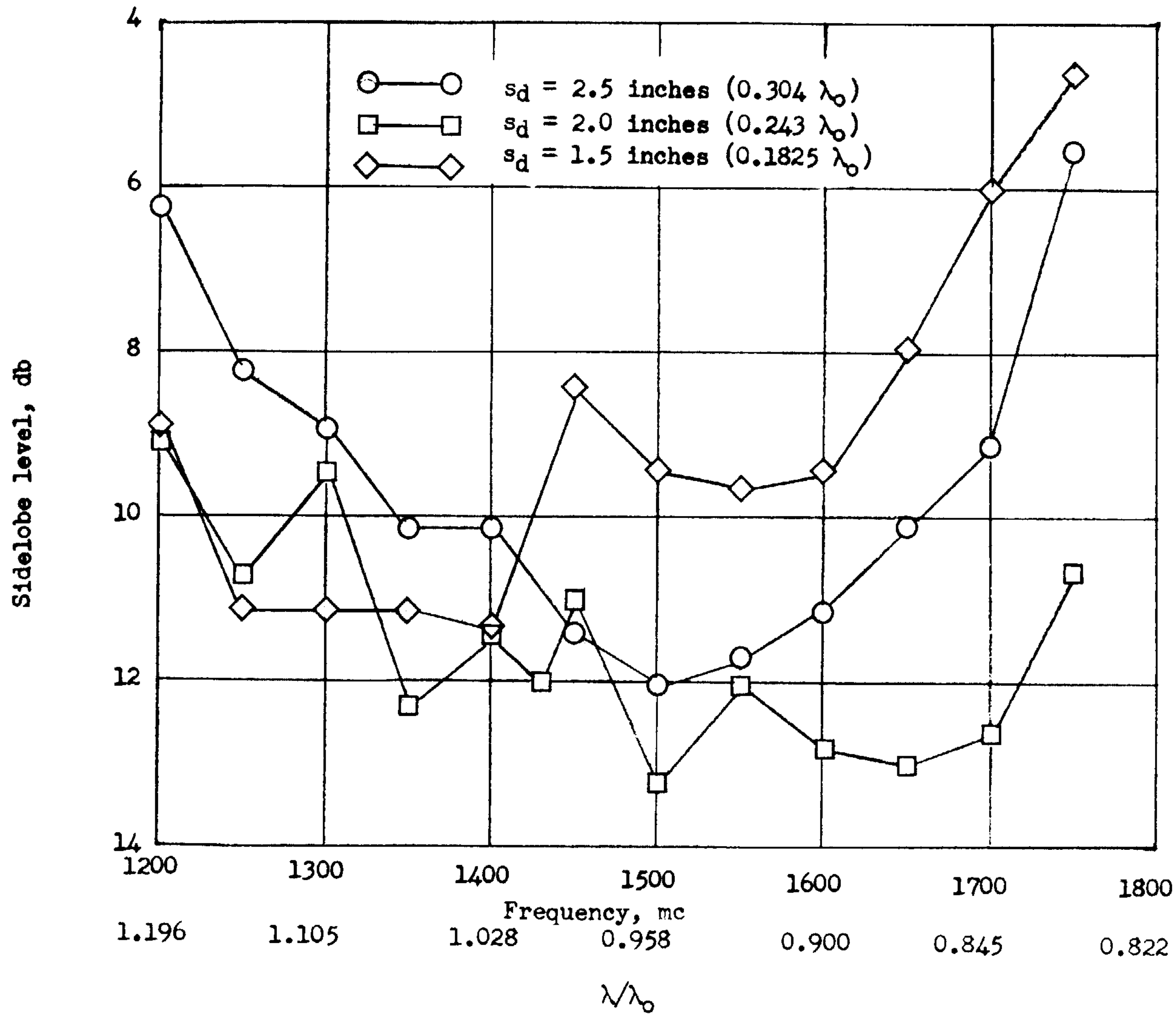
(b) Packaged. L-61-4836

Figure 15.- Concluded.



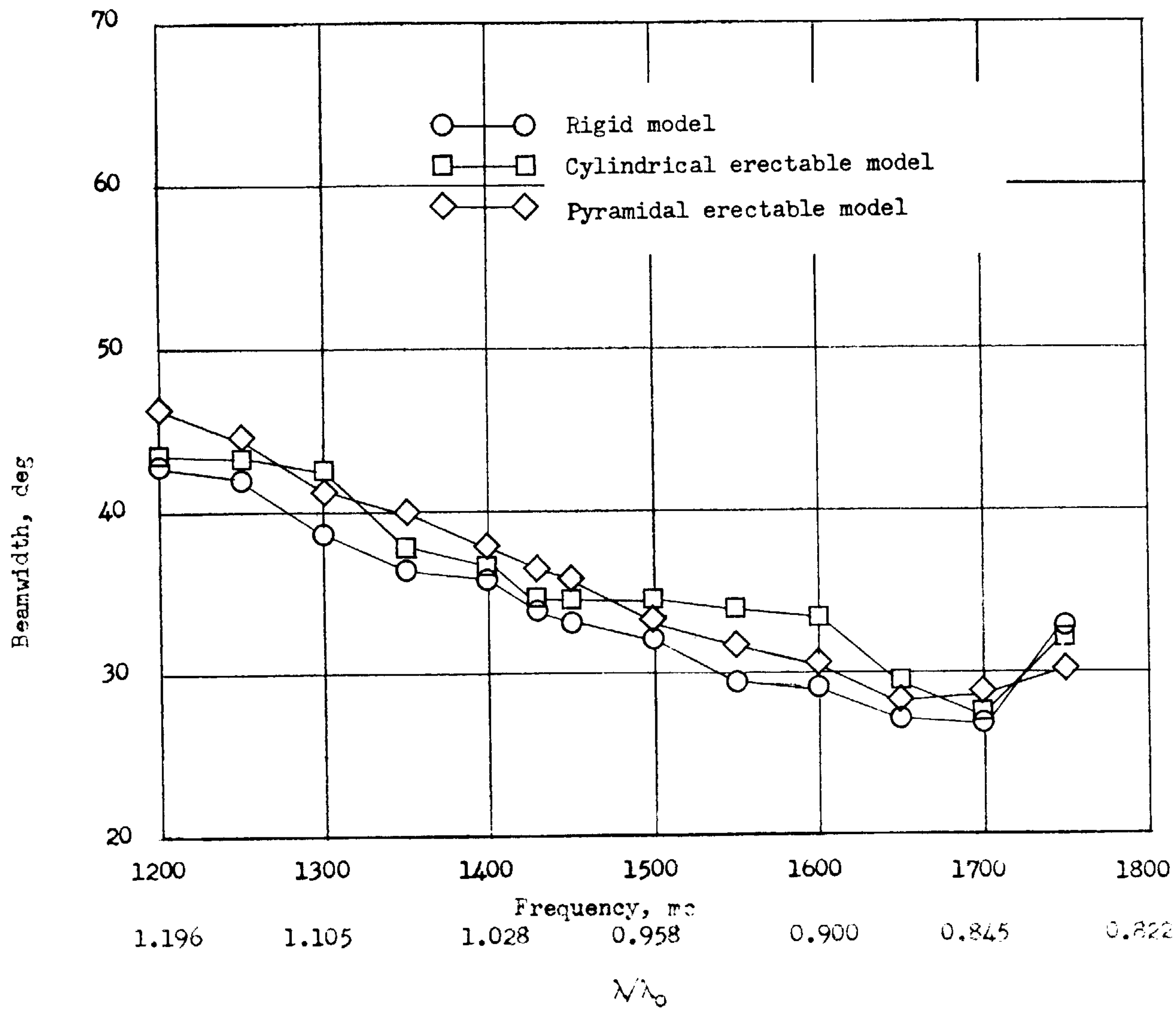
(a) Array beamwidth (E and H plane average) as a function of frequency.

Figure 16.- Effect on array characteristics due to changes in disk spacing.



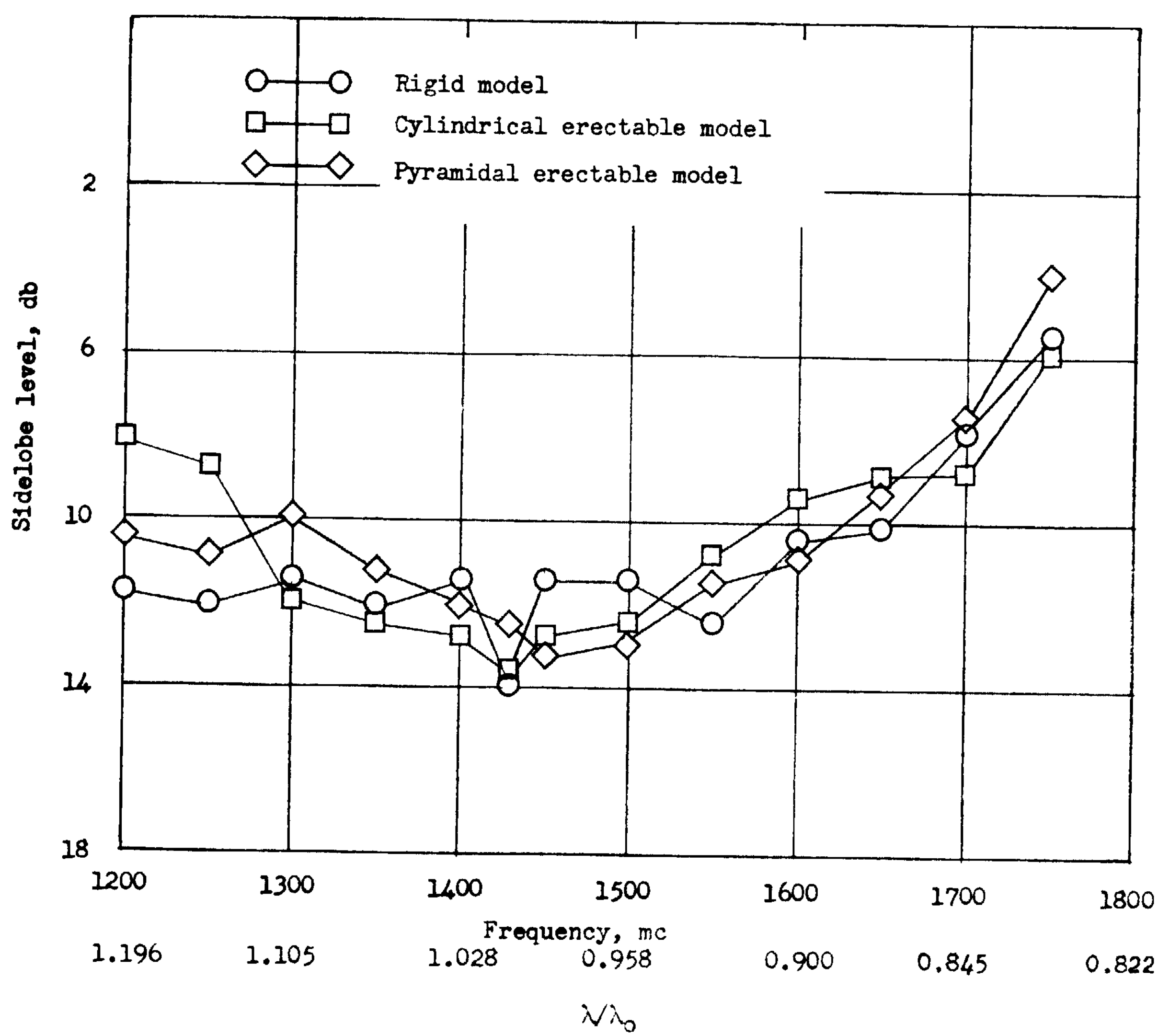
(b) Array-sidelobe level (maximum value) as a function of frequency.

Figure 16.- Concluded.



(a) Beamwidth (E and H plane average).

Figure 17.- Comparison of rigid and erectable models.



(b) Sidelobe level (maximum value).

Figure 17.- Concluded.

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